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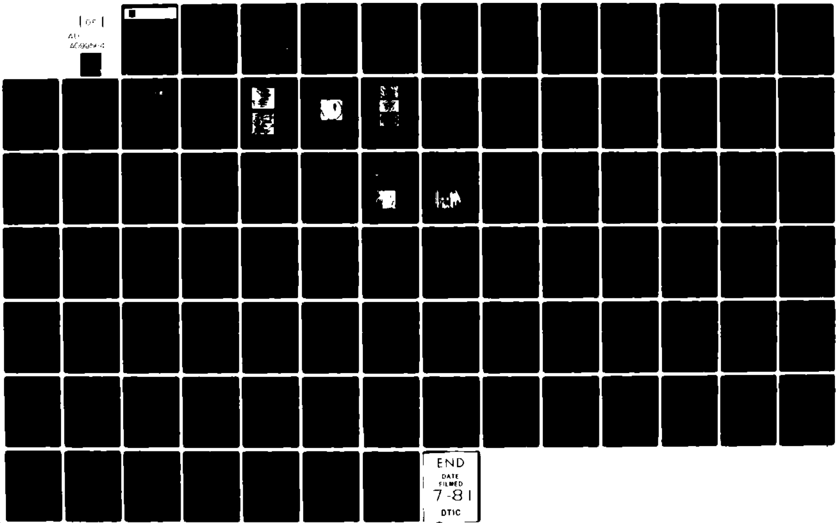

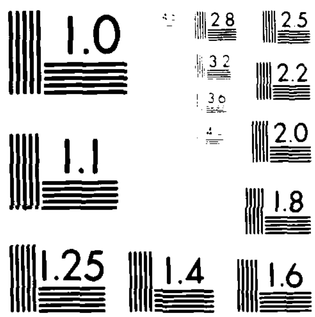

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Research in Sea Ice Mechanics

Panel on Sea Ice Mechanics
Marine Board
Assembly of Engineering
National Research Council

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PANEL ON SEA ICE MECHANICS
MARINE BOARD
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PANEL ON SEA ICE MECHANICS

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PREFACE

For a number of years, the Marine Board has been concerned with the national ability to support engineering activities in and under the ice of the polar oceans. An urgent object of the concern is the projected increase in operations in Alaskan offshore waters demanding offshore structures and marine transportation systems, principally for petroleum exploration and production.

An understanding of sea ice mechanics is essential to the design and integrity of cost-effective structures and fundamental to operating in the polar oceans. In recognition of this, the National Research Council appointed the Panel on Sea Ice Mechanics, in 1979, to investigate the available information and research needs in this area. The committee defined the scope of its interest to include the whole state of knowledge of sea ice mechanics, but to stop short of in-depth analysis of physical and environmental forces, such as wind and waves, that directly affect the mechanics of sea ice.

The panel chose to limit consideration of research needs to the mechanics of ice masses on the scale of the engineered structures that could be introduced into the natural icescape. These may range in size from a few meters to several hundred meters or longer in the case of causeways. The panel did not consider mechanics on a large scale of tens of kilometers. The geophysical motions of sea ice, as driven by winds and ocean currents, that would figure in such large-scale studies are important in determining the loads ultimately imposed on engineered structures in a sea-ice environment. Nevertheless, an examination of the mechanics of sea ice and its oceanic and atmospheric driving forces would involve an investigation considerably different in character and would emphasize other disciplines. Likewise, the other extreme of spatial scale, the behavior of single crystals of sea ice, is not addressed in this study, because such an investigation would not be linked directly to engineering activities.

While many of the engineering problems posed by river and lake ice are similar to those of ice mechanics at sea, the panel chose to address basic relationships not made more complex by the variations attending fresh and salt water or the addition of other constituents to the sea and ice environment. In regard to the snow-ice (or soil-ice) problems that can be encountered offshore, the panel chose to treat these as subsets of ice types.

The panel's study was conducted under the guidance of the Marine Board and with the cooperation of the Polar Research Board. It was sponsored by the U.S. Departments of the Interior, Commerce, State, and Energy, and the U.S. Coast Guard, Navy, the Army Corps of Engineers, and the National Science Foundation through a general support contract administered by the Office of Naval Research.

The panel met four times--twice in Seattle, Washington, and twice at the National Academy of Sciences in Washington, D.C.--over a ten-month period to review the nature and extent of sea ice mechanics research and to assess the gaps in knowledge of the field that need further study in order to advance the safety of structural and facility design in ice-covered offshore areas. In its assessment, the panel did not suggest research priorities, since many of the interrelationships between various long-range research efforts and their engineering benefits cannot be rigorously established.

This report reviews what is known about the nature of sea ice and its processes, the interaction of ice masses and structures, and recent and on-going research needed in model ice--using other materials to simulate ice characteristics in laboratory-scale tests--and artificially made sea ice. The report draws conclusions and recommendations in its last section.

SUMMARY

This report identifies gaps in knowledge and understanding of the physical and engineering properties of natural and man-made ice. The panel offers recommendations for scientific and engineering research to provide data for the design of offshore and shoreline structures, as well as for the design of marine transportation systems for operations in ice-covered regions. While a leading motivation for increasing knowledge of sea ice mechanics is Alaskan offshore oil and gas development, research results may be applied to any offshore site or area affected by ice.

Sea ice mechanics is concerned, in general, with the interaction of environmental forces of oceanographic and meteorologic origin with an ice cover at sea, and the manner in which such forces are transmitted to other ice masses and eventually to man-made structures. Important aspects of the subject include the mechanical origins of deformation features, such as cracks, leads, pressure ridges, and rubble fields, and the mechanical properties of ice sheets and the bulk properties of large ice masses.

The interaction of the ice cover with fixed and moving structures was identified by the panel as an important subject for research. Important ice types include sheet ice, ridges, rubble, fragmented covers, frazil ice and brash ice. Additional field observations, analytical studies, and laboratory model studies are needed to better understand the formation, mechanical behavior, and interaction of ice aggregates with engineering structures.

Sea ice is a complicated material, consisting of crystals of pure ice, solid salts, and liquid-filled brine pockets. The mechanical properties of sea ice have been studied for many years, but our understanding is still largely qualitative. Most small-scale test results are inconsistent and gaps remain in the data. Large-scale properties have proved difficult to measure. Scaling factors for model tests have not been well defined.

The panel recommends that laboratory tests be conducted to obtain mechanical characteristics of sea ice with appropriate internal states. Experiments should be conducted to determine the large-scale mechanical characteristics of natural sea ice cover of known internal state, and theories should be developed to provide satisfactory properties essential for engineering design.

The interaction of sea ice types with fixed and moving structures is fundamental to the basis of the engineering design and operation of offshore structures. The mechanical behavior of sea ice aggregates, as they interact with structures, is not well understood. Therefore, the panel recommends that further knowledge of the mechanical behavior of sea ice aggregates be obtained through field observations. Laboratory studies should be conducted to better understand the formation and interaction of ice aggregates with engineering structures. Analytical studies combining field observations and laboratory experiments with the basic laws of mechanics should be conducted to develop theoretical models of the mechanical behavior of various ice types.

Much of our understanding of ice processes and the interactions of ice and structures will be derived from small-scale model tests. The panel recommends that a systematic research program be conducted to investigate the properties of different materials for modeling ice such as synthetics, doped ice, or paraffin. The feasibility of using model ice to determine the large-scale mechanical properties of ice features also should be investigated.

The panel concludes that a systematic approach to sea ice research at the national level will require an integration of government and private planning, long-term research, contractual commitments, and the interpretation of research missions in relation to national needs. The government needs to increase its sea ice research efforts by stating a clear commitment to their pursuit, coordinating the activities of the several agencies with an interest in results, promoting the dissemination of research results, and attracting more investigators into the field. The panel hopes this report will stimulate these actions and thus expand the adequacy and availability of information and expertise on sea ice mechanics in the public domain.

The panel recommends that one government agency be designated to lead and coordinate all federal work in sea ice mechanics technology. The agency needs to include in its programs research to answer, in cooperation with other agencies, the pressing engineering problems of sea ice mechanics. To attract additional people to the field, a long term commitment should be made by the government to support sea ice mechanics research. This should include the development of courses, workshops, symposia, and textbooks in the field. A single agency should act as a clearinghouse to facilitate public access to the results of government and industry research.

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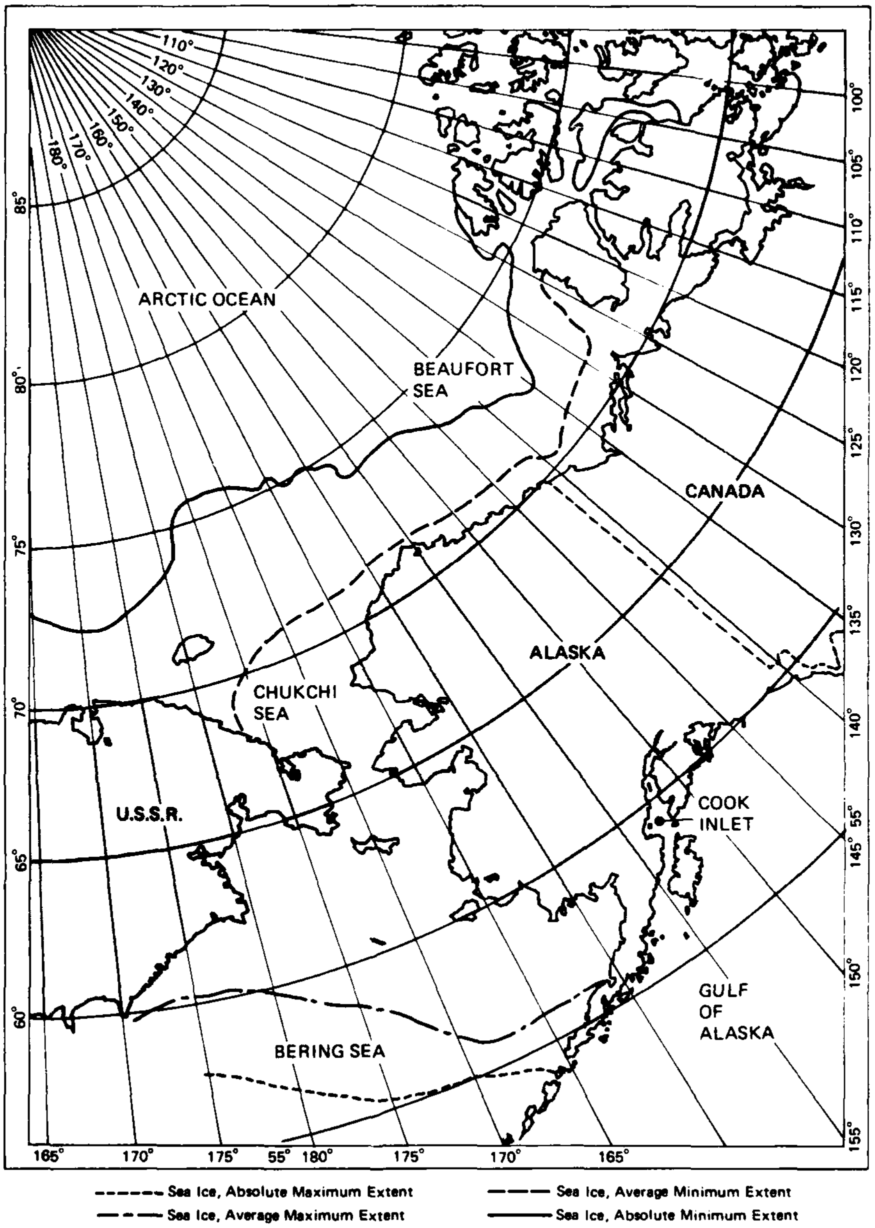


Alaskan Arctic Seas and
Extent of Sea Ice

Source: American Geographical Society, New York, New York, 1975.

INTRODUCTION

Sea ice covers 10 percent of the earth's ocean during part of the year (Barry 1980).[1] In spite of the abundance of this natural material, its mechanics are not well understood. Man, for reasons of comfort and safety, has preferred to avoid sea ice.

In the next several decades, exploration for energy resources in the sea off Alaska and Canada, and the possible production of these resources, will challenge engineering and technology in icy conditions.

The enormity of this region is daunting for its remoteness, environment, and sheer size. The Alaskan coastline is approximately as long geographically as the Pacific and Gulf of Mexico coasts of the United States.

Recent estimates of the U.S. Geological Survey indicate that of the total undiscovered domestic oil and gas reserves, approximately 60 percent of the oil and 50 percent of the gas may lie in areas of offshore Alaska affected by ice (USGS, 1980).[2] The combined areas of the sedimentary basins within which hydrocarbons presumably occur under the ice-covered arctic waters is several times larger than those explored by drilling in the Gulf of Mexico.

The requirements for arctic offshore development emphasize the need to better understand the nature and interaction of environmental forces of oceanographic and meteorologic origin and sea ice, and the transmission of these forces to other ice masses and man-made structures. Better understanding of sea ice phenomena also would advance shipping, fishing, and other human activities in severely cold climates.

SECTION I
DESCRIBING SEA ICE

This chapter provides a description of sea ice. In order to gain an engineering understanding of sea ice, it is necessary to consider the characteristics and mechanics of sea ice at two scales. At the small-scale, sea ice can be described as a material in terms of growth, structure, and composition. At a large-scale, sea ice is an aggregate of individual pieces of ice. The aggregate has important unique characteristics and needs to be described in terms of the dynamics and mechanics of the ice cover.

Sea Ice as a Material

The structure of first-year sea ice is similar to that of a cast ingot (see Figure I-1). The size and orientation of the first crystals that form depend upon the sea state at the time of formation. Turbulence favors the formation of small equigranular crystals while large plate-like crystals grow in calm water. Once an initial ice skin has covered the sea, the crystals grow downward, compete at the growing interface, increase in size, and acquire a preferred orientation. Each crystal consists of alternating layers of pure ice and layers containing ice and liquid filled brine pockets. The optical C-axis of the hexagonal sea ice crystal is normal to these layers (see Figure I-1). Those crystals which grow most rapidly have their C-axis horizontal so that the direction of easiest growth is vertical and parallel to the direction of heat flow. The result is a rapid increase in grain size in the upper portion of the ice cover associated with a tendency for grains with horizontal or near-horizontal C-axis orientation to become dominant. This portion of the ice sheet, where rapid changes in crystal orientation occur, is called the transition zone. The base of the transition zone is commonly less than 30 cm below the upper surface of the ice sheet.

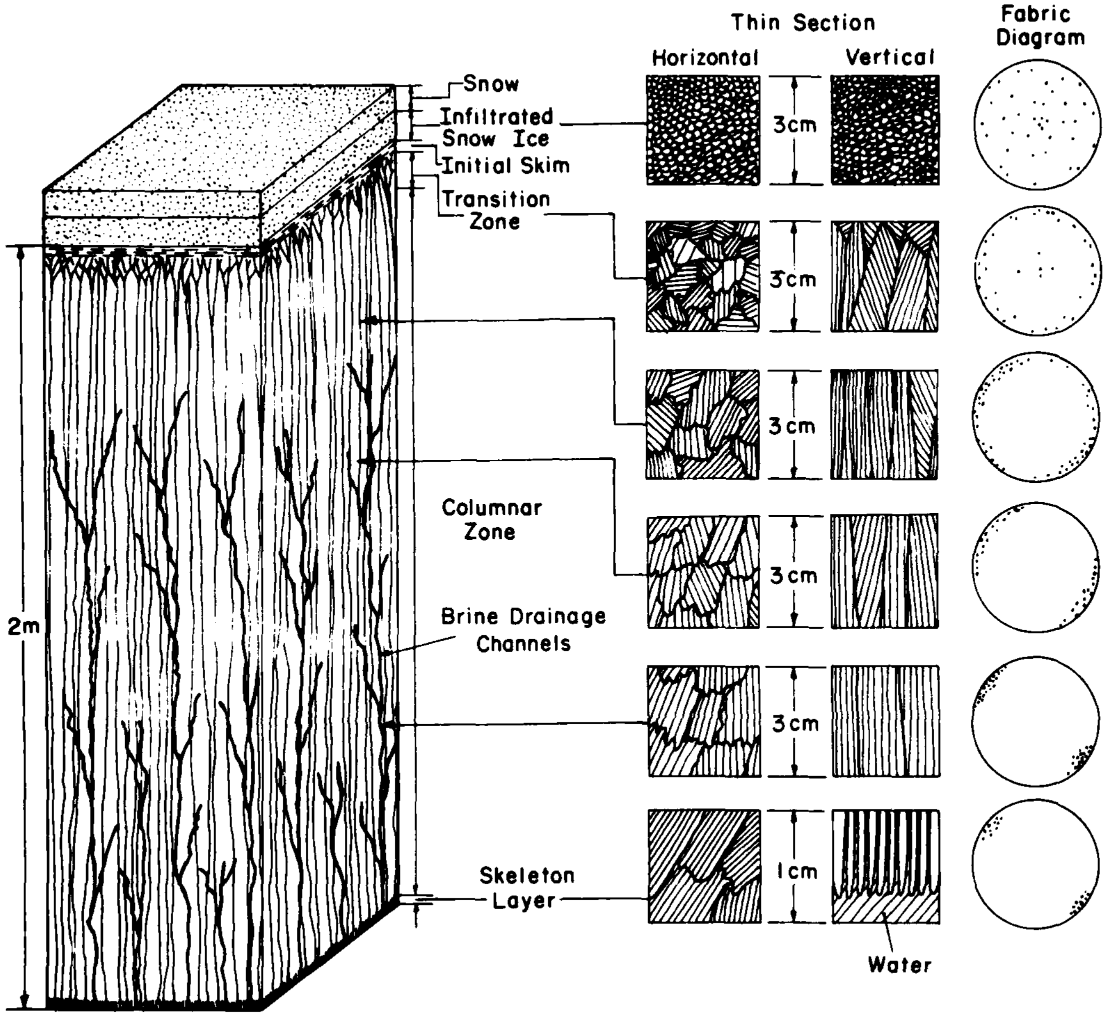


Figure I-1

Several Aspects of First-Year Sea Ice Structure

Note: The fabric diagrams are representatives of the orientation in space of the C-axes at each depth in the ice sheet. These show the progressive transaction from randomly oriented cyrstals, represented by the scatter of points in the diagram for the top of the ice sheet, to strong alignment of nearly horizontal C-axes in a northwest-southwest direction at the base.

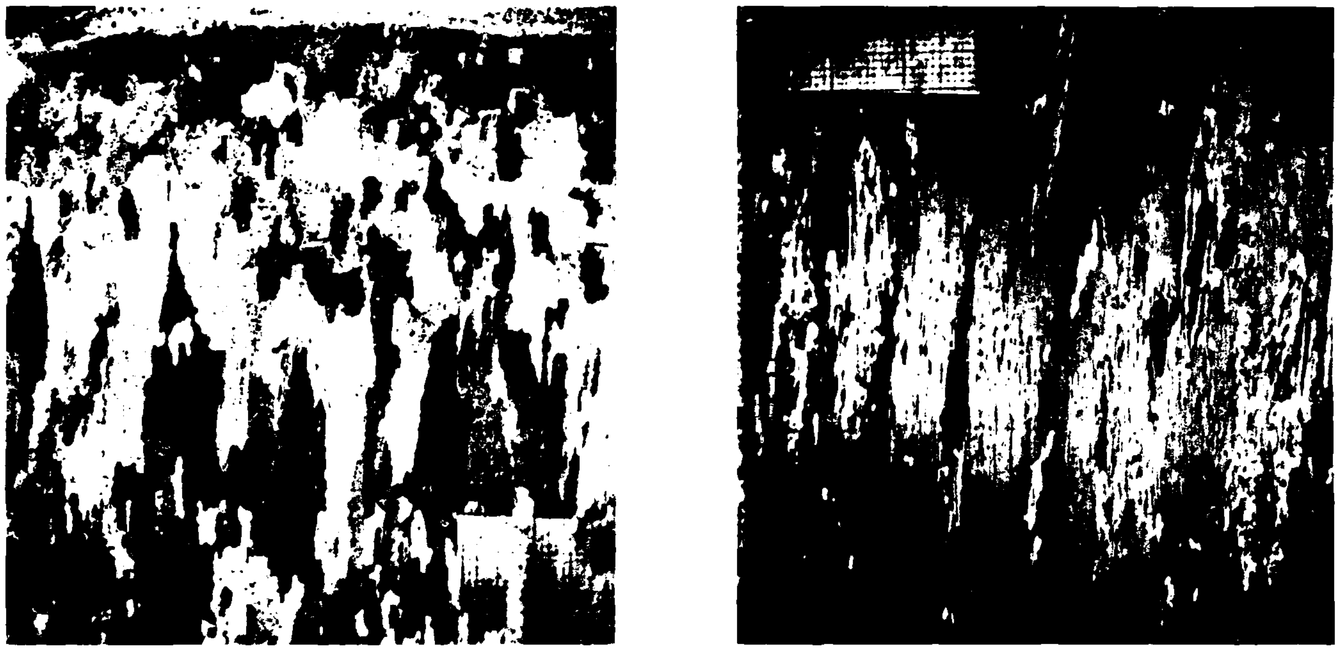
Source: W. F. Weeks

Below the transition zone is the columnar zone. It has a fairly uniform structure with the crystals showing horizontal C-axis orientation and a pronounced crystal elongation parallel to the direction of heat flow. Weeks and Assur (1967)[3] give a number of figures showing the structure of the initial skin, the transition zone, and the upper part of the columnar zone. Figure I-2 shows a vertical thin section which illustrates these structural elements.

For many years, it was believed that the crystals in the columnar zone invariably showed C-axis horizontal orientations that were random in the horizontal plane. In fact, such a structure has been documented at a number of locations. Such a material would be described as transversely isotropic in that it shows a variation in properties in the vertical direction, but all directions in the horizontal plane are equivalent. However, recent studies (Weeks and Gow, 1978, 1980; Kovacs and Morey, 1978)[4,5,6] have revealed that the great majority of the ice occurring over the continental shelves of the Arctic show strong C-axis alignments within the horizontal plane. The apparent factor in controlling the direction of these alignments is the direction of the current at the ice-sea water interface. These roughly colinear alignments appear to extend over large distances relative to a typical grain diameter and give the ice a variation in properties along three orthogonal axes.

In addition to these variations in gross crystal shape, size, and alignment, there are pronounced variations in the internal structure of the individual crystals of sea ice. Every crystal is subdivided into a number of ice platelets that are joined together to produce a type of quasi-hexagonal network as viewed in the horizontal plane. This structure is clearly shown in Figure I-3, a photomicrograph of a horizontal thin section of sea ice. Similar substructures are common in metals produced by the directional solidification of impure alloys (see, for instance, Chalmers, 1964).[7] They result from crystal growth in which the solid-liquid interface is non-planar, causing the entrapment of impurities within the boundaries of these substructures. In fact, the salt in sea ice is entrapped in brine pockets, or liquid inclusions that are located along these substructures. Figure I-4 shows representative photomicrographs of an array of such brine pockets. The spacing between brine pocket arrays (measured parallel to the C-axis) varies inversely with the growth velocity (Lofgren and Weeks, 1969)[8] and is commonly referred to as the plate spacing. As might be anticipated, these variations in plate spacing also have an effect on the mechanical properties of the ice (Weeks and Assur, 1963).[9]

Associated with the variations in the freezing velocity and in the composition of the sea water being frozen, there are variations in the amount of salt (brine) that is entrapped within sea ice. These interrelations have been studied by Weeks and Lofgren (1967);[10] they are quite systematic, and are also similar to related occurrences in metals and ceramics. The salinity of the ice is a linear function of the composition of the sea water with very fast growth incorporating



(a) (b)

Figure I-2

Vertical thin sections (crossed polaroids) of (a) the upper 10 cm and of (b) a portion of the columnar zone (76 to 85 cm) of a sheet of first-year sea ice from the Chukchi Sea near Barrow, Alaska.

Source: W. F. Weeks and S. J. Gow

Figure I-3

Photomicrograph of Horizontal Thin Sections
of First-Year Sea Ice

Source: Schwarz, J. and Weeks, W. F. (1977) "Engineering Properties of Sea Ice," J. Glaciology 19(81), pp. 499-531.

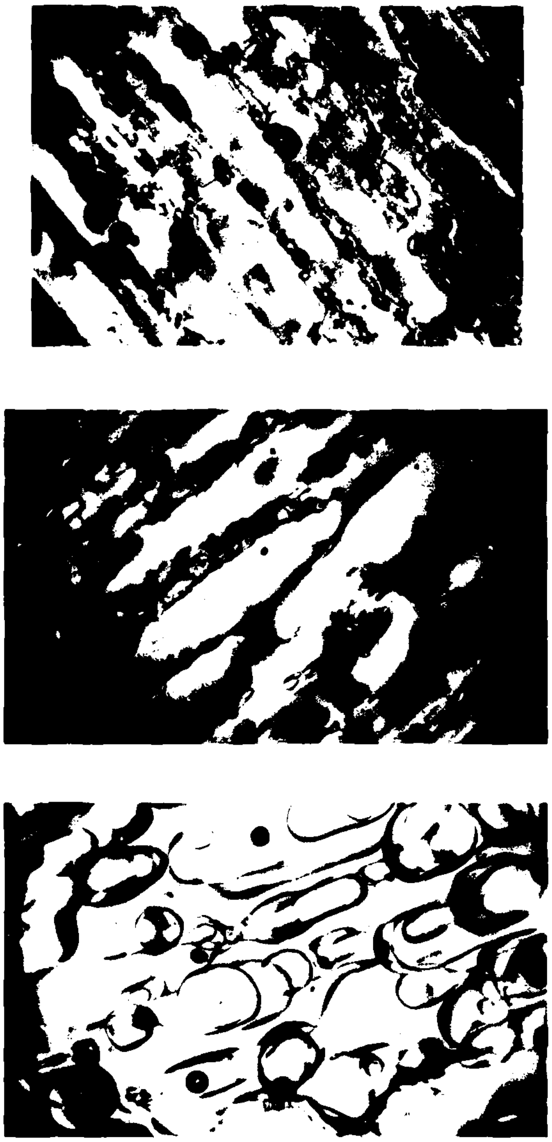


Figure I-4

Photomicrographs of sea ice showing details of brine pockets. The spacing between brine pockets is approximately 0.5 mm.

Source: W. F. Weeks

the majority of the salt into the ice and very slow growth resulting in near-total salt rejection. Once salt has been entrapped in sea ice, it gradually drains out. This is a complicated process (Cox and Weeks, 1974, 1975; Niedrauer and Martin, 1979)[11,12,13] that is, as yet, only partially understood. Typical salinity profiles for first-year ice are given in Figure I-5. Such profiles show a consistent C-shape and also change systematically with ice thickness.

As the brine in the ice drains down and out, structural features caused by this drainage develop. These are called brine drainage channels (Lake and Lewis, 1970),[14] and can be thought of as tubular river systems in which the tributaries are arranged with cylindrical symmetry around the main drainage channels. Near the bottom of thick annual ice, drainage channels appear to occur on a horizontal spacing of 15 to 20 cm and have a diameter of approximately 1 cm. Such features obviously affect the mechanical properties of sea ice, but their effect has, as yet, not been quantified.

The amount of brine in sea ice, or brine volume, ν , is determined by the ice salinity and temperature. As either the ice salinity or temperature increases, the ice brine volume increases to maintain phase equilibrium between the ice and brine. This variation is most pronounced near the melting point where small changes in temperature result in large changes in the brine volume (Assur, 1958).[15]

Numerous studies have shown that the strength, modulus, and other properties of sea ice are strongly influenced by the ice brine volume (Weeks and Assur, 1969; Schwarz and Weeks, 1977).[16,17] The results of many sea ice strength tests suggest a relationship of the general form

$$\frac{\sigma_f}{\sigma_o} = 1 - c\nu^k$$

where σ_f is the ice failure strength, σ_o is the hypothetical strength of sea ice at zero brine volume, and c and k are constants which depend on the geometry of the brine inclusions. The constant k is commonly found to be equal to 1/2. Thus the strength of sea ice varies as the square root of the brine volume. The results of many modulus tests also show a brine volume dependency. The modulus of sea ice, E, varies linearly with the brine volume, that is

$$\frac{E}{E_o} = 1 - d\nu$$

where E^o is the hypothetical modulus of sea ice at zero brine volume, and d is a constant that depends on the geometry of the brine inclusions.

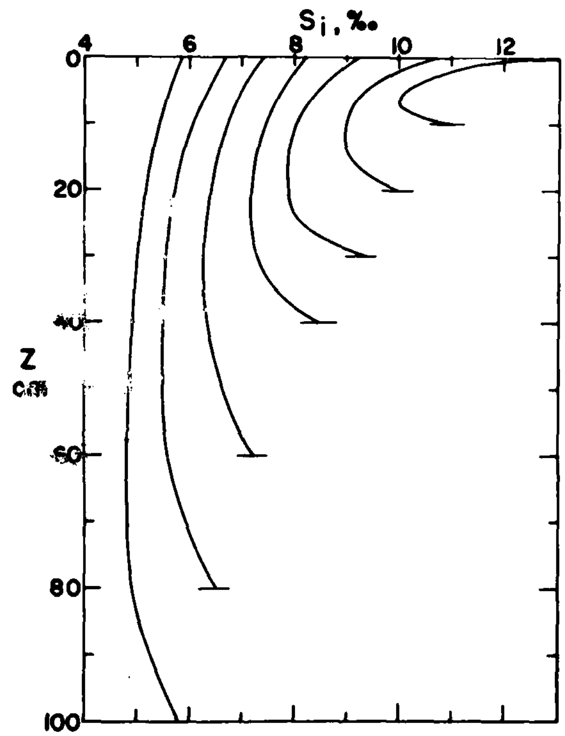


Figure I-5

Typical Salinity Profiles for First-Year Ice of Various Thicknesses

Source: W. F. Weeks

Since the ice salinity and temperature vary with depth in an ice sheet, so do the ice brine volume, strength, and modulus. Figure I-6 illustrates how σ_f and E might vary in 0.2, 0.8, and 3.0 m thick ice sheets.

There are also a variety of solid salts that form in cold sea ice (Assur, 1958).[18] The crystallization temperatures of the two most common salts are -8.7°C ($Na_2SO_4 \cdot 10H_2O$) and -22.7°C ($NaCl \cdot 2H_2O$). Peyton (1966)[19] reported that the crystallization of these solid salts has a pronounced effect on the mechanical properties of sea ice. However this finding has not been supported by subsequent work and, until well defined tests are performed, such an effect will remain speculative (Weeks and Assur, 1969).[20]

First-year sea ice, subjected to a period of summer melt, undergoes a pronounced change in salinity. This is largely caused by the percolation of relatively fresh surface melt water downward into the ice (Untersteiner, 1967).[21] This flushing results in salinity profiles such as that given for the 3.0 m thick ice in Figure I-6. There is also the possibility of recrystallization in the upper part of such ice floes. Ice that has survived a number of summers ultimately becomes a layer cake of the annual layers that are formed during successive winter periods of ice growth. Ultimately multi-year ice reaches an equilibrium (approximately 3 to 4 m in the central Arctic Ocean) such that the thickness ablated during the summer equals the thickness grown during the winter (Maykut and Untersteiner, 1969).[22] Considering the vast amount of multi-year ice present in the high Arctic, its properties have been little studied. In particular, the strength data appear to be contradictory in that some results suggest that multi-year ice is appreciably stronger than first-year ice while other data show little difference.

The impression of differences between the properties of ice and those of other materials is, to a large part, the result of the fact that sea ice exists in nature and is usually studied at temperatures within a few degrees of its melting point while experience with other materials is commonly at temperatures far removed from their melting point. Studies of sea ice may provide insight into the behavior of many other materials at or near their melting point.

Development and Change of Sea Ice Cover

The traction of wind and currents on an ice cover causes it to move and deform resulting in the formation of cracks, leads, pressure ridges, and rubble fields. Cracks and leads may freeze and produce new areas of thin ice, while pressure ridges and rubble fields may consolidate and result in areas of much thicker ice. Icebergs and ice islands from glaciers and ice shelves are also incorporated into the ice and further increase the variation and complexity of the ice cover. In coastal areas and shoals, large ice features ground on the sea floor and, as a result of movement of the surrounding ice sheet, they produce gouges on the sea floor. Ice can also pile-up on or completely over-ride coastal features.

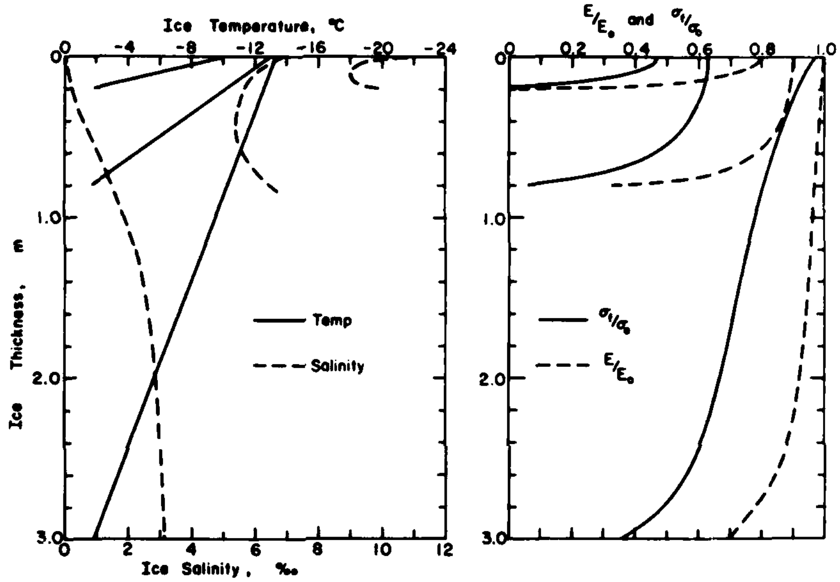


Figure I-6

Variations in Ice Salinity, Temperature, Modulus, and Strength with Ice Thickness

Thickness of 0.2, 0.8, and 3.0 m, arctic sea ice, 1 May.

Source: Schwarz, J. and Weeks, W. F., (1977) "Engineering Properties of Sea Ice," J. Glaciology 19(81).

Sea ice can take many forms. Level ice occurs in the range of sizes from continuous sheets to dispersed, fragmented covers of discrete, relatively small floes. Deformed ice occurs as pressure ridges, rubble fields, and floebergs. The ice forming any of these features can be either first-year or multi-year ice. To enable the design process, and engineer needs to understand the bulk mechanical properties of both first-year and multi-year ice.

The features can be divided into two categories; the first category is consolidated features, such as sheet ice, large floes, multi-year ridges, and floebergs. The properties required for these features are those of the various constitutive laws that are used to describe the deformation of a continuum. The remaining features, such as first-year pressure ridges and rubble fields, and fragmented ice covers, constitute a second category which is essentially unconsolidated aggregates of fragments of ice of various sizes. In these cases, it is the bulk properties of the aggregate which is of interest to the research person and engineer.

Once a sea ice cover has formed, it commonly undergoes a variety of processes that may produce significant changes in both its external and internal structure. The most important of these processes are mechanical, as compared to the essentially thermodynamic processes described earlier, and are largely the result of the differential motion of one segment of ice relative to another.

If sea ice were motionless, ice thicknesses would be controlled completely by the thermal characteristics of the lower atmosphere and upper ocean. Such an ice sheet would have a thickness and physical properties that change slowly and continuously from region to region. However, even a casual examination of almost any area of sea ice reveals striking lateral changes in ice thicknesses and characteristics. These changes are invariably caused by ice movement. For an initially continuous piece of sea ice to move away from the shore, a break must occur that will allow separation. This occurs with the formation of cracks. If a crack opens to a width sufficient to sail a ship through, the resulting open water area is referred to as a lead. There have been few detailed studies of such cracks in sea ice (Evans and Untersteiner, 1971; Evans 1971),[23,24] but some knowledge of their behavior has been gained from field observations. The cracks form very rapidly (possibly propagating at near-sonic speeds); they appear to be insensitive to ice thickness in that they cut right through areas of thicker ice without noticeable deflections, and they can extend for tens, and perhaps hundreds, of kilometers. The fact that a crack has formed does not necessarily mean that a lead will develop. Many cracks separate a few centimeters and then refreeze. However, this also is a subject that has been little studied. During most of the year in the polar regions, once a lead is formed it is immediately covered with a thin skin of ice that thickens with time. Therefore, in a region of pack ice where leads are continually forming, the development of leads provides a mechanism for generating a wide variation in ice thicknesses with the thickest undeformed ice being the oldest. The compass orientation of a set of leads may change over a period of a few hours as the result of the movement of weather systems; one set of leads may become inactive and be replaced by another set oriented in quite different directions.

Just as important as the opening of leads is their closing. When this occurs, the thin ice in the leads is broken and pushed into a variety of piles, so-called pressure ridges. There are a number of varieties of these features, some of which characteristically form in thin ice, some in thick. In a general way, there are two primary types of pressure ridges: p-ridges caused by closures essentially normal to the lead and s-ridges (so called shear ridges) are produced by motion parallel to the lead. These two ridge types show a number of characteristic differences. P-ridges have a sinuous surface trace and are composed of blocks having dimensions related to the thickness of the ice being incorporated into the ridge. Such ridges are also often associated with large (many tens of meters) over- and under-thrusts of the interacting ice sheets. S-ridges are straighter and characteristically have one vertical side. They are composed, primarily, of highly granulated ice a few centimeters or less in diameter, and variable quantities of rounded ice "boulders" of dimensions up to the thickness of the ice sheets from which the ridge was formed. The properties of the ice in ridges will be discussed later, but a few points should be made now. In a general way, p-ridges are primarily composed of the thin (or thinner) ice from refrozen leads. This is a simple reflection of the fact that when the ice pack comes under compression, it is the weakest (thinnest) material that is deformed first. However, as a lead rarely closes exactly as it opened, there are commonly areas of the thinner lead ice left even after rather severe deformation. Generally, larger ridges are composed of thicker ice, and occasionally very thick multi-year floes interact together to produce ridges.

Extensive rafting usually occurs in the vicinity of p-ridges. It is not uncommon to find rafted ice thicknesses 2-4 times the sheet thicknesses within a distance of a few hundred meters of the ridge. In some cases, the rafted ice is broken into blocks and incorporated in the ridge.

The heights of ridge sails and the depth of ridge keels have been studied using laser and sonar profilometry respectively (Weeks et al., 1971; Tucker et al., 1979).[25,26] The distribution functions are exponential--there are many small ridges and large ridges are rare. The largest free floating sail height and keel depth (not the same ridge) currently on record are 13 m and 47 m respectively (Kovacs and Mellor, 1974).[27] In general, keel depth statistics appear to be scaled up versions of sail statistics (which have been more extensively studied since it is easier to obtain such data) with a depth to height ratio of 4 to 5/1.

When pressure ridges survive a melt season, the interblock voids that characterize newly formed ridges are first filled with relatively fresh water produced by surface melting of the ice. This water then freezes, bonding the ice blocks together into massive low-salinity multi-year pressure ridges. (Kovacs et al., 1973; Wright et al., 1978).[28,29]

In many cases ice deformation does not result in discrete ridges; instead the complete ice sheet is converted into a wasteland of heaps of ice blocks (Kovacs, 1972).[30] This type of chaotic terrain is called a rubble field. Many times the surface relief on a rubble field is only two to four meters high. However, a field may be composed of rows upon rows of ridges like the furrows of a plowed field, each row having six to eight meter sails. When such large rubble fields survive a summer, they become welded into extremely massive bodies of low salinity ice. Such formidable ice masses have been studied off the Beaufort Sea coast where they were grounded in 17-18 m (56-59 ft.) of water and had a maximum freeboard of 12.6 m (41 ft.) (Kovacs, 1976).[31] It is generally believed that large rubble fields and shear ridges are more frequent near coasts than within the main pack. However, there are no quantitative observations on this subject.

Recent work has also shown that, at least off the North Slope of Alaska, the ice within approximately 150 km of the coast is more highly deformed than the ice in the central pack of the Beaufort Sea (Tucker et al., 1979; Wadhams and Horne, 1978).[32,33] Aircraft observations (Wittmann and Schule, 1966)[34] suggest that this is generally true along the margins of the Arctic Ocean from northeast Greenland to the Chukchi Sea.

A particular problem associated with near shore ice conditions is caused by grounding. Such groundings plough deep gouges in the sea floor sediments (Barnes and Reimnitz, 1974; Lewis, 1977).[35,36] Gouges in excess of one meter are fairly common. Lewis (1977)[37] reported rare gouges in the Canadian Beaufort Sea of up to 7.6 m. In addition, when an ice pile-up grounds, the fact that it is building upon a solid foundation may allow the sail to pile-up to impressive heights of 30 meters or more. Also, major pile-ups can occur on beaches, and at times ice can completely override low islands. A useful summary of observation and theory relative to the occurrence of such events can be found in Kovacs and Sodhi (1980).[38]

Brief mention should also be made of ice islands and icebergs even though they are ice in the sea and not sea ice in the true sense. Nevertheless, they do pose significant hazards in areas where they occur. The origins of icebergs are well known, and they are largely a problem of the eastern Arctic, in particular in the region between Greenland and Canada, where they present major problems to offshore operations. The "icebergs" of the Arctic Ocean are called ice islands. These are, in fact, fragments that have broken off a relict Pleistocene ice shelf that exists along the north coast of Ellesmere Island in the Canadian Archipelago. The best known ice island, T-3, has been drifting around the Arctic Ocean for over 30 years. The thicknesses of ice islands and ice island fragments are quite variable as they gradually ablate during their drift. T-3 showed an initial thickness of approximately 70 m. The lateral dimensions are also highly variable, ranging from in excess of 10 km in the case of the very large examples such as Ward Hunt 5, which at one time completely blocked Robeson Channel between Greenland and Ellesmere Island, to a few tens of meters for ice island fragments. No detailed studies have been made of the mechanical properties of the ice comprising ice islands. Much of this ice reportedly has many similarities with glacier ice which has been well studied. However, a wide variety of ice types have been noted (Smith, 1964),[39] some of which resemble lake ice and some sea ice. Perhaps the most needed information on ice islands is improved observational data on their number, location, and size distribution. This would allow realistic estimates to be made of the encounter probabilities between such features and offshore structures.

Finally, some mention should be made of the rates at which sea ice could be expected to move against structures. The drift and acceleration rates of an ice mass are the result of wind drag, water drag, wave forces, and interaction with other ice masses. Thus, knowledge of ice drift need not be totally dependent on direct observation; it can be bolstered by modeling of these forces. As would be expected, there are wide variations in observed sea ice drift rates with mean annual net drift rates varying from 0.4 to 4.8 km/day with the actual rates (including loops and other irregularities) as high a 2.2 to 7.4 km/day (Dunbar and Wittmann, 1963).[40] Most studies of drift rates involve ice located within the main pack of the Arctic Ocean. In general, speeds are low in the winter when the ice cover is tight and high in the summer when the pack opens up. Highest drift rates are invariably found near the edge of the pack where the ice is moving under nearly free-drift conditions, that is where there are few ice to ice interactions. For instance, during storms ice drift rates of as much as 40 kilometer per day have been noted in the Bering Strait (Shapiro and Burns, 1975),[41] and similar rates have been observed near the southern part of the East Greenland Drift Stream (Wadhams, 1980).[42] For most offshore operations data are required for near shore areas, and some information is available on this subject. For instance, off the Beaufort Sea coast of Alaska, data have been collected by bottom connected systems in areas of fast ice (Agerton and Kreider, 1979),[43] radar ranging systems in the very near shore pack (Tucker et al., 1980),[44] and satellite positioning systems further offshore (Martin et al., 1978).[45] Offshore from the barrier islands, which line much of this coast, movements during the winter are small and tend to occur in discrete events associated with strong offshore winds of several days duration. In protected fast ice, motions are commonly less than a few tens of meters over an entire winter and also usually occur in short discrete events. However, even during the winter, major ice movements can occur at some locations during storms. For instance, Shapiro (1975)[46] has observed ice drift velocities of 8 km/hr. for a 5-hour period at Barrow during the winter (associated wind velocities were as high as 90 km/hr.).

SECTION II
INTERACTIONS BETWEEN SEA ICE AND ENGINEERED STRUCTURES

This section describes the interactions between sea ice and engineered structures from an engineering standpoint. It identifies the physical properties and processes that must be considered in designing structures for a sea ice environment. In the next chapter the state of knowledge of sea ice mechanics is reviewed, and research needs are identified.

Ice and Modeling Considerations in the Engineering Design Process

When designing for a sea ice environment, the engineer is concerned with the mechanical properties of an undeformed ice sheet, and also with the large scale mechanical properties of the ice cover and bulk properties of ice features. The ice deformation processes and properties of interest depend on the type of ice feature and type of structure, vessel, or equipment in contact with the ice.

Design criteria for new engineering concepts are generally developed by a combination of field measurements and experience, analytical work, and model tests. Field experience applicable to arctic structures is available from the installation and maintenance of lighthouses and bridge piers in northern waters, the Cook Inlet production platforms that were installed in the mid 1960's, artificial islands that have been used for exploration drilling in the Beaufort Sea, floating drilling operations in the deeper waters of the Canadian Beaufort Sea, and floating ice platforms between the Canadian Arctic islands. The characteristic ice conditions that are applicable to the design of a particular structure depend on the location and intended use of the structure as well as the physical characteristics of the structure.

Analytical estimates of ice forces are usually based on some constitutive assumptions for the ice, environmental driving force estimates, a geometric description of the ice, and the boundary condition between the ice and the structure. Analytical approaches frequently strive to bound, rather than predict, ice forces, since the amount of information needed to establish a bound is substantially less than that required for a detailed description of the actual process. If the bound is not overly conservative, it may be adequate to establish a design load.

As an example, consider a floating ice beam that is pushed against an inclined structure. There are several possible ways in which the ice beam could fail. Three possibilities illustrated in Figure II-1 are:

1. The ice could fail in bending as it slides up the surface of the structure.

2. The ice could fail by crushing if the in-plane stresses reach the crushing load.

3. The ice could fail by buckling if the in-plane stresses reach the buckling load.

Each of these failure modes would require different information on the ice material characteristics in order to quantify the force that would be associated with the failure mode. In order for any of the three to actually occur, it is necessary that the ice be sufficiently strong so that other failure modes (including possibilities that may not be listed) would not occur prior to reaching the load required for the failure mode under consideration. It is also necessary that the environmental driving force or driving displacement be sufficiently great to create the failure mode. Hence, quantifying the load needed for any of the possible failure modes establishes a bound for the actual ice failure load, and the lowest calculated load would be the closest to the actual load. The conservativeness of each bound would depend on the values of the particular parameters. The buckling load in the above example is proportional to $h^{3/2}$, where h is the ice beam thickness, and the crushing load is proportional to h. The slope angle and ice/structure friction coefficient significantly affect the bending load. The bending failure mode would be eliminated for a sufficiently steep slope and the buckling and crushing possibilities would remain. A thin ice beam would be expected to buckle and a force estimate for the buckling mode would be most appropriate. A thick ice beam would be expected to crush rather than buckle.

The bending failure load would be affected by the frictional sliding resistance at the ice/structure contact region and by the bending strength of the ice in the presence of the in-plane load. Likewise, the crushing load would depend on the ice crushing strength. Since ice strengths are rate dependent, both failure loads

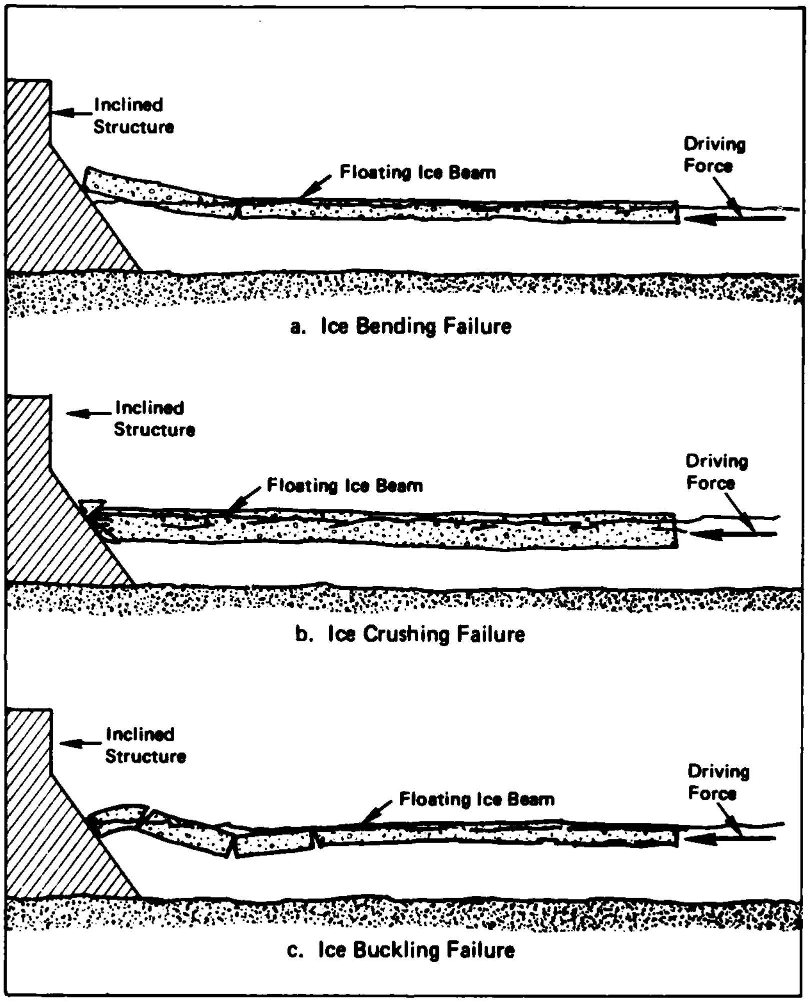


Figure II-1

Interaction of a Floating Ice Beam with an
Inclined Structure

Source: Panel on Sea Ice Mechanics

would depend on the rate at which the environmental driving forces moved the beam against the structure. The buckling load, on the other hand, does not depend on ice strength properties. It is determined by the constitutive behavior of the ice prior to failure, e.g., knowledge of the elastic modulus would be sufficient for an elastic idealization of the buckling load.

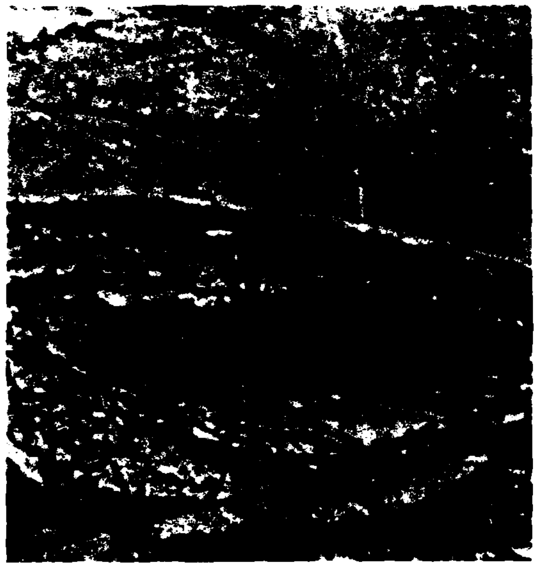
Model tests are generally conducted to address a particular failure mode. The ice properties that are applicable to the failure mode are identified and scaled by the model ice material. It is not generally possible to adjust all model ice properties to the same scale factor. However, even if all properties are not exactly scaled, if the model failure mode is identical to that of the prototype, and the model ice properties are measured, model test results still provide valuable information for verifying analytical predictions. Most model studies have addressed ice bending failure against structures with the model material properties adjusted to represent the bending strength and bending modulus of the ice. This work has been a relatively straightforward extension of prior work for ships in ice. Modeling difficulties typically arise when a particular failure mode is not well defined. The process that creates an ice rubble pile is an example of a mixed-mode failure in which different ice properties may be important at different stages of the process.

Gravel Islands

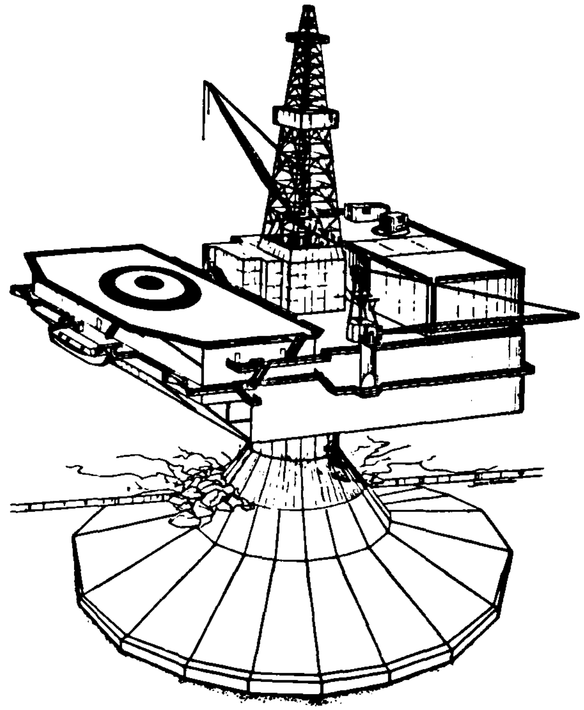
Gravel islands, such as that shown in Figure II-2(a) have been used for exploration drilling platforms in both the Canadian and Alaskan Beaufort Sea. Seventeen man-made islands have been constructed in the MacKenzie Bay area in water depths ranging from less than two meters to as deep as 20 meters. Three man-made gravel islands have been used as drilling platforms in the shallow near shore area of the Alaskan Beaufort Sea and similar designs have been proposed for application in the December 1979 lease area (Technical Seminar, 1979).[47]

The surface geometry of man-made islands have been either circular or rectangular, depending on the construction season and the desired layout of the drilling equipment. Typical working surface dimensions are of the order of 100 m to 150 m. The slope of the island beach depends on the construction mode and may range from 1:3 for a sandbag protected beach to 1:15 or greater for an unprotected dredged beach.

Ice conditions near gravel islands consist of extensive movements of thin ice during freeze-up, of rotten ice during break up, and slow ice movements of limited extent in the stable winter landfast ice. The ice activity during freeze-up depends on location. In relatively protected areas, freeze-up ice movements may create a small ridge or rubble pile, or some override of thin ice on the island beach. Freeze-up movements can be very extensive in exposed areas, and create ice ride-up on island beaches or large rubble piles surrounding the



(a)



(b)

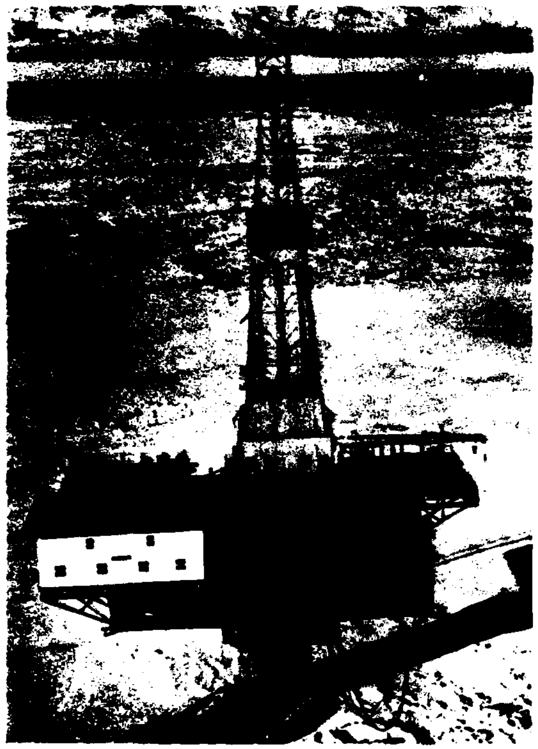
Figure II-2

a. Gravel Island Platform in the Beaufort Sea

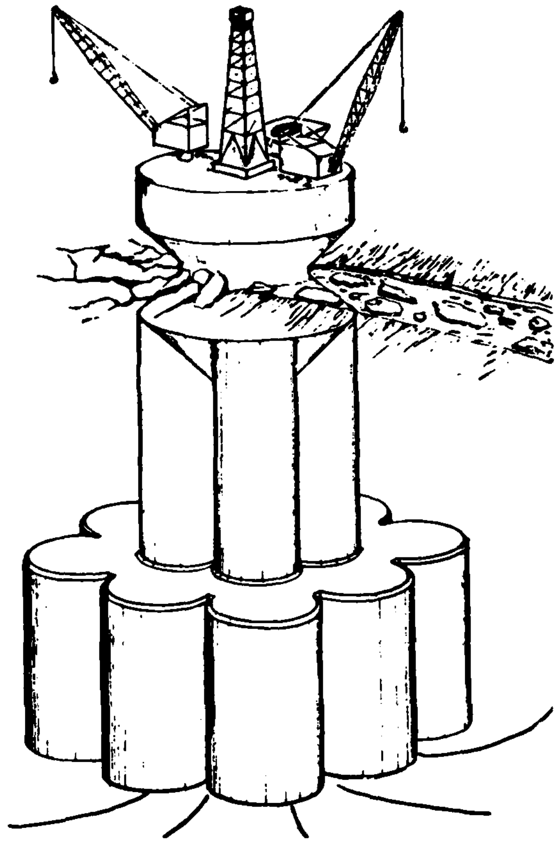
Source: Exxon Company USA

b. Conceptual Design of a Conical-Shaped Drilling Platform

Source: J. Hancock and P. H. Scherpe (See Reference #55)



(c)



(d)

Figure II-2

c. Monopod Production Platform in Cook Inlet

Source: Brown and Root, Inc.

d. Conceptual Design of an Ice-Breaking Caisson Production Platform

Source: K. A. Blenkarn (See Reference #58) island. The rubble may be several island-widths in diameter and have an irregular surface topography. Local heights of rubble 13 m above the water surface have been observed at some locations (Kry, 1977).[48]

Winter ice conditions around gravel islands have, in general, been stable, with slow ice movements of limited extent. Typical events may consist of ice movement rates of a few feet per hour and excursions of the order of tens of feet. The movement of the winter ice creates an active zone of ice failure at the exterior of the rubble pile. Since the rubble surrounds the island, the total force created by ice failure in the active zone is balanced by the sum of the force transferred through the grounded rubble to the sea floor and the force transmitted through the rubble to the island. Field measurements of ice forces in the smooth ice near the active zone have been made at a number of islands. However, there is little information available on transfer of forces through the rubble and into the sea floor and island (Technical Seminar, 1979).[49]

Ice breakup activity usually occurs in late June and early July. At this time, the ice has partially melted and is in a warm deteriorated state. The deterioration usually begins near river outlets and along the coastlines. After the ice is essentially free of the coastline, large movements of the deteriorated ice can occur in response to the local wind conditions.

Design Considerations and Ice Properties

The two principal ice design considerations for gravel islands are ice forces and over-ride. During freeze-up the ice properties relevant to the ice/structure interaction include the following:

Ice/Beach-Ice-Rubble Friction Coefficients
: These factors limit: (a) the ability of ice to ride up the slope of an island, (b) the extent of ice rafting, and (c) the ability of an ice sheet to over-ride a rubble pile. The ice/beach friction coefficient would depend on the beach protection material.

Bending Strength/Buckling Properties
: The ice rubble formation process creates bending and buckling failure of the sheet ice.

Unconsolidated Rubble Bulk Properties
: The bulk strength and deformation characteristics of the newly-formed rubble, together with the local ice movement characteristics, determine mine the geometry of the rubble pile that will surround an island during the winter season. The resistance of the grounded portions of the rubble determines the extent of rubble formation that will remain at the island following ice movements from several directions.

Winter ice loads are developed by movement of the sheet ice against the rubble pile that surrounds the island. The properties of interest are:

Large-Scale Compressive Sheet Ice Strengths
: If the rubble pile is sufficiently competent, the load applied to the rubble/island combination can be limited by the large-scale compressive failure of the ice. In addition to needing to know the unconfined compressive strength of sheet ice, the two-dimensional strength response that develops under natural ice deformation processes also needs to be determined.

Large-Scale Buckling Strength of Sheet Ice
: The large-scale buckling strength of sheet ice also limits winter ice loads.

Sheet Ice Bending Strength
: If the rubble is not sufficiently competent, the sheet ice will penetrate the rubble and be subject to out-of-plane loads and bending failure.

Ice Rubble Bulk Properties
: The bulk strength and deformation characteristics of the partially refrozen ice rubble together with the rubble pile geometry determine the relative proportion of the applied ice sheet load that is transmitted to the island and to the sea floor. The bulk rubble properties also determine whether the ice sheet will penetrate or compress the rubble or crush at the sheet ice/rubble boundary.

Conical Structures

As indicated in Figure II-2(b), (page 23), conical structures employ an inclined surface to apply vertical loads to floating ice and create bending failure. This approach uses the relative weakness of ice bending strength compared to its crushing strength and leads to a significant reduction in forces for conical structures compared to vertical structures. Field experience with conical-shaped structures is available from several decades of lighthouse operations in the St. Lawrence waterway (Danys, 1977)[50] and actual field measurements from an instrumented test structure off the coast of northern Japan (Oshima et al., 1980).[51] Conical structures deployed in the Arctic would be exposed to considerably thicker ice than that experienced by existing structures and several projects involving model tests, (Arctec, Inc., 1972)[52] analysis, (Ralston, 1980)[53] and design studies (Jazrawi and Khanna, 1977; Hancock and Van Scherpe, 1979)[54,55] have been conducted in recent years to address arctic applications. A typical base dimension of an arctic cone structure is of the order of 100 m. A typical waterline diameter would be of the order of 30 m. The angle of the conical slope and its ice/structure frictional characteristics determine the ratio of the horizontal and vertical forces that are applied to the structure. The total ice force can be thought of as consisting of an ice breaking force and an ice clearing force. The breaking force arises from the failure of the floating ice that advances against the structure while the clearing force results in the removal of the previously broken ice from the surface of the cone.

Design Considerations and Ice Properties

The ice features that a conical structure would be designed to resist depend on the geographical location. First-year ridges, rubble fields, and annual sheet ice represent winter ice design conditions throughout most of the Bering Sea. In the Chukchi and Beaufort Seas, multi-year ice in the form of floes and ridges is present along with annual sea ice features. Ice loading can occur at any time of the year in areas that are subject to summer ice invasions.

The principal design considerations that result from these ice conditions are the horizontal and vertical ice forces and over-turning moment and the distribution of local ice pressure in the ice-contact region. The design of the upper surface of the structure would consider the kinematics of ice clearing to minimize ice jamming and to determine the elevation of the deck. The ice properties of interest include the following:

Large Scale Bending Strength

The full-thickness bending strength of annual sheet ice, consolidated rubble and rafted ice, multi-year floes, and multi-year ridges is directly related to the forces imposed on an inclined structure. The magnitude of the in-plane load that is applied along with the bending moment would depend on the geometry of the structure.

Ice/Structure Friction Coefficient

The sliding resistance between the ice and the surface material of the cone has a significant effect on the magnitude of the horizontal ice force.

Ice/Structure Adfreeze Strength

The advantages of ice bending failure on inclined structures may not be achieved if a frozen bond between the ice and the structure prevents bending failure. The magnitude of this frozen bond may be controlled by the use of special coatings or heating.

Warm Ice Crushing Strengths

The distribution of ice contact pressures on the surface of an inclined structure depends on the crushing behavior of the ice. In particular, the strength of near-melting sea ice which occurs on the bottom of a multi-year ridge will determine the pressure distribution when the ridge initially contacts the structure.

Tower/Caisson/Steel Jacket Structures

In mild sea ice areas, such as the southern Bering Sea, production platforms similar to those used in Cook Inlet may be constructed. Fourteen permanent production platforms were installed in Upper Cook Inlet between 1964 and 1968. Thirteen of these platforms resemble the jacket-type structures found in the Gulf of Mexico. Eleven are four-legged structures and two are three-legged structures. To reduce the effects of ice loading, the cross bracing on these structures is omitted in the vicinity of the waterline. In order to gain the required strength, the legs of these structures are larger than normal--typically of the order of 4.5 meters diameter. The structures are pile founded with each leg containing from eight to twelve piles. The piles also serve as conductors for the wells. The fourteenth platform in the inlet is the Monopod, the platform shown in Figure II-2(c), (page 24). The deck of this structure is supported by a single cylindrical shaft 8.7 meters in diameter, which is attached to a large base. The foundation support is provided by pilings that are attached to the base or driven through the walls of the cylindrical shaft.

Cook Inlet is noted for its dynamic winter ice conditions. Ice movement within the inlet is dominated by the 6- to 8-knot tidal currents that move the ice rapidly against the legs of the structures at strain rates where the ice is well into the brittle range. Thus the entire range of ice strain rate loading conditions is experienced with each tidal cycle. The highest ice forces have been reported during the slack tidal period when the ice movements are relatively slow (Goepfert, 1969).[56]

The largest ice forces are generated by pressure ridges in Cook Inlet. These peak loads are reported to be two to three times the sheet ice loads (Blenkarn, 1970).[57] Ridge thicknesses of the order of 3 to 6 m are observed in the Inlet. The ridge forces result from the consolidated, or solid, portion of the ridges. Presumably, the consolidation is a combined result of the re-freezing and bonding of rubble in the upper portion of the ridge and the effect of rafted ice within the ridge.

Design Considerations and Ice Properties

The principal ice design considerations for tower-like structures are ice pressure ridge forces, dynamic ice/structure interaction for both sheet ice and ridges, and possible ice jams between the legs of multi-leg structures. The ice properties of interest include the following:

Bulk Pressure Ridge Properties
: These properties, including those of re-frozen rubble and rafted ice, are most significant in determining the maximum ice forces. They also help determine the leg spacing necessary to prevent ice jams from interferring with the ice clearing action between the legs of a multi-leg structure.

Sheet Ice Compressive Strengths
: The rate-dependent aspect of sheet ice strength in sequential failures is applicable to dynamic ice/structure interaction.

Floating Structures

Floating structures have application as exploration and production platforms in deep ice covered water. The use of floating ice platforms for exploration drilling between the Canadian Arctic islands is an example of a floating structure which resists vertically applied loads but does not resist lateral forces. The mechanics of floating ice structures will be discussed later in this section under the topic of "Artificial Ice and Ice Structures." The use of an ice resistant floating caisson structure illustrated in Figure II-2(d), (page 24) has been proposed for deep water drilling and production applications (Gerwick and Jahns, 1979).[58] The conceptual design included a double-cone configuration near the waterline to break ice in bending and found the downward breaking capability to be most effective in reducing ice loads. Other features, such as actively induced heaving, have also been investigated in model tests.

Design Considerations and Ice Properties

The major ice design consideration for a floating structure is to control ice forces so that the motion of the structure remains within its operational limits. The ice features of interest are sheet ice and pressure ridges. The ice properties of interest are similar to those of conical structures, for example:

Bending Strength (either upward or downward)
The bending strength and ice/structures friction coefficient would control the sheet ice loads during extensive sheet movements.

Adfreeze Strength
If the ice is allowed to freeze to the structure during extended periods of no motion, the strength of the adfreeze bond can be significant.

Bulk Ridge Properties
The largest loads would be expected to result from pressure ridge forces.

Submerged Structures

Submerged structures such as pipelines, well-heads, and water intakes, can either be protected from ice action by burial or be designed to withstand submerged ice forces. Exploration wellheads, from floating drilling operations in the Canadian Beaufort Sea, have been placed in an 11 meter-deep hole in the seafloor with the top of the wellhead 4 meters below the original mud line to prevent damage to ice keels (O'Rourke, 1979).[59] The selection of a burial depth for either pipelines or wellheads depends on the local ice and soil conditions which limit the ice scour depth. An arctic seafloor pipeline has been completed at Panarctic's Drake F-76 gas well off the east side of Melville Island (Marcellus and Palmer, 1979).[60] In the near shore area, the pipeline was buried and backfilled. The pipe bundle was strengthened by circulating a coolant to artificially freeze the soil below the pipeline and the backfill above it. Tests indicated that the compressive strength of the frozen soil was 100 times that of the unfrozen soil.

Design Considerations and Ice Properties

Warm ice properties are of interest for estimating loads applied to submerged structures. The types of properties (compressive strength, bending strength, etc.) would depend on the geometry of the ice feature and that of the structure, but the temperature of the ice would be expected to be very close to the water temperature. Depending on the geographic location, the properties of both first-year ice and multi-year ice, as well as the bulk properties of ridges and rubble, are of interest to the engineer.

The presence of free-floating ice crystals in the water column pose potential clogging and other operational problems for water intakes located in northern environments. Most intake field experience is available for the operation of fresh water rather than sea water intakes; however, plans exist for the construction of a sea water intake near the Prudhoe Bay oil field. Long term development of offshore oil reservoirs would possibly require similar sea water intake capabilities.

Artificial Ice and Ice Structures

Artificial sea ice has proven to be a useful construction material and a solution to several engineering problems. Artificial ice structures are constructed by the controlled flooding of sea water on the ice surface. This technique has been used to build a number of structures, including ice roads and bridges (Kivisild et al., 1978);[61] ice runways and aircraft parking aprons (Dykins et al., 1962;[62] Dykins et al., 1962;[63] Kingery et al., 1962);[64] ice wharves (Barthelemy, 1975;[65] Kirkpatrick, 1974);[66] floating ice drilling platforms (Baudais et al., 1974;[67] Masterson and Kivisild, 1978);[68] and grounded drilling ice islands (Utt, 1978;[69] and Cox, 1979).[70]

Design Considerations and Ice Properties

In many applications, the design and construction of these ice structures requires an understanding of the constructed ice thermal and mechanical properties of the constructed ice, and for floating ice structures, the mechanical behavior of surrounding ice sheet. A knowledge of the thermal properties is often needed to predict ice buildup rates and the temperature and strength of the resulting ice (MacKay, 1970;[71] Cox, 1979).[72] As brine has been found to accumulate at the constructed-natural ice interface (Masterson and Kivisild, 1978),[73] a better understanding of brine migration and removal would be helpful. For floating ice structures, the bearing capacity and deflection of the surrounding ice under both static and dynamic loads are important (Masterson and Kivisild, 1978;[74] Kivisild et al., 1978).[75] The feasibility and design of grounded ice structures subjected to lateral ice loads requires a knowledge of the shear strength of the high brine volume constructed ice near the base of the island and the sliding resistance (coefficient of friction) of the island on the sea floor (Cox, 1979).[76] Specifically, shear strength data are needed for flooded ice, flooded-snow ice, and ice constructed by spraying. Tests should be conducted to determine the effects of strain rate and confinement. Such tests are difficult to perform in that data are needed for warm, saline ice which is difficult to sample, machine, and test without significant brine drainage.

Ports and Maritime Operations

Ice problems associated with port and terminal operations in northern environments can be classified as operational problems and structural problems. The structural problems are similar to those previously discussed for other types of offshore structures. The operational problems are mainly those associated with the management of broken ice to minimize interference with vessel operations (Cammaert et al., 1979).[77] Ice management techniques can be thought of as procedures for ice suppression, icebreaking, ice removal, and ice diversion.

Techniques for ice suppression usually involve transporting heat, providing insulation, or accelerating natural processes (e.g., ice dusting) to inhibit or suppress the growth of ice. The thermal properties of sea ice are relevant to these techniques.

Ice breaking provides a channel for vessel passage. The use of icebreaking vessels is the most proven technique. However other possible approaches include air-cushion vehicles, mechanical cutters, chemicals, steam, and explosives. The mechanical properties of ice that are important for these techniques include those relevant to icebreaking as well as the specific cutting and fracture energies.

The mechanical properties of interest in ice removal processes are the bulk properties of ice rubble. The piece sizes of interest may range from the large pieces produced by an icebreaker to ice chips contained in a slurry that may be piped from an ice management area.

Ice diversion is generally a rigid body process which would be relatively independent of ice properties, however specific procedures, such as the use of ice anchors, may require some knowledge of ice properties.

Vessel operations in ice covered waters are concerned with route selection and feasibility and the interaction of vessels with the ice. The statistical description of ice coverage, ridge distributions, ice physical characteristics, and internal pressure state are related to route selection; however these questions are beyond the scope of problems addressed by this panel.

The main thrust of sea ice mechanics in aiding maritime operations involves the interaction of vessels with the ice. The problems are associated either with vessels actively moving through an ice cover or with stationary vessels (e.g., moored at a terminal), which are loaded by a moving ice field.

The forces exerted on a vessel moving through a level ice sheet have been thoroughly studied and are reasonably well understood. Route selection procedures generally strive to avoid ice ridges and select a route through level and, if possible, thin ice. Ice ridge interactions with vessels are not as well understood. When avoidance is not possible, vessels may transit a ridged area by sequentially ramming the ridges until breakthrough is accomplished. Such procedures are costly in terms of both time and fuel.

Vessels can be successfully moored in the presence of ice, provided that the ice cover is sufficently well broken. Canmar's floating drilling operations in the Canadian Beaufort Sea provide some field experience with moored vessels that are subjected to moving ice fields (O'Rourke, 1979).[78] Their operational procedure is to actively create a sufficiently fragmented ice cover such that the resultant loads on the vessel are less than the mooring line capabilities.

In addition to the over-all ice forces, which determine operational capability, local ice pressures on the hull of a vessel are important for detailed design consideration. Considerable uncertainty remains in the specification of local ice pressure magnitudes as a function of loaded area for ice breaking vessels. This criterion determines the local framing and hull thickness needed to transfer the local loads developed on the hull.

Design Considerations and Ice Properties

Sheet ice properties (bending strength, bending stiffness, and crushing strength) are of interest for normal vessel operations in level ice and for estimating local ice pressures acting on the hull. The aggregate properties of fragmented ice covers are of particular importance for determining mooring requirements for stationary vessels subjected to moving ice fields. The bulk properties of ice ridges, and a description of the mechanics of their interaction with vessels, are needed for optimal route selection and for performance predictions for areas that are subjected to ice ridge and rubble formation.

Significant sea ice mechanics research areas to improve maritime transportation operations are: the interaction of ridges and non-level ice with vessels; the moving aside of broken ice by a vessel; passage of vessels through broken ice--normal pressures and resulting friction, in which brash ice is one element; ice pressures on vessels; mechanics of ship propellor-ice interactions; brash ice characteristics, including friction, refreezing rates, mechanical properties; and, hull-ice impact forces, mechanisms, and magnitudes.

In Situ Stress and Strain Measuring Devices

Stress and strain measurements made in the field provide fundamental information on the natural processes that occur in sea ice (Templeton, 1979; Prodanovic, 1978).[79,80] The basic measurement problem--how does the presence of the transducer affect that which is being measured--differs for the two kinds of measurements. Strain measurements are achieved by measuring displacement over a known gauge length with the intent of keeping the disturbance caused by the presence of the transducer to a minimum. Surface strain measurements are relatively straightforward, however internal strain measurements present some difficulties associated with installation and interaction of the ice with the transducer.

In situ stress measurements are made with an embedded sensor. Since the mechanical properties of the sensor are different from those of the ice, the transducer represents an inclusion in a host material. The stress measured by the sensor is the result of the interaction of the sensor with the ice. The extent of the interaction is generally localized and the undisturbed stress (or that which would exist if the sensor were not present) is the quantity that is to be estimated by the measurement.

The nature of the interaction between the sensor and the ice depends on the sensor geometry and the difference in the mechanical properties between the sensor and the ice. The effective ice stiffness is an important parameter, however its value depends on the loading process. Hence, it is necessary to either design the sensor to be relatively insensitive to ice stiffness variations or be able to estimate the ice stiffness by some other means in order to infer the undisturbed stress.

Design Considerations and Ice Properties

Ice strength and ductility properties are of interest in the design of an embedded transducer since the interaction stress field could lead to a structural failure of the ice near the sensor at undisturbed stress levels that do not approach failure. The constitutive response of the ice prior to failure is also important, since the range of possible effective ice stiffness values is an important input parameter in the design of a sensor.

The thermal expansion characteristics of sea ice are important if simultaneous *in situ* measurements of stress and strain are used to observe natural ice loading events. These events may occur over time periods of hours or even days in the landfast ice of the Beaufort Sea and may be accompanied by large temperature changes. Therefore, it is necessary to be able to separate out the thermal and mechanical components of ice deformation if the stress-strain behavior of the ice is to be quantified.

SECTION III
STATE OF KNOWLEDGE AND RESEARCH NEEDS

This report has described sea ice as a material, and also in the aggregate. It then reviewed the interactions between sea ice and engineered structures and identified the physical properties and processes that must be considered in designing structures for a sea ice environment. The objective of this chapter is to review the state of knowledge of sea ice mechanics to determine what is known relative to the broader aspects of ice mechanics including the basic need to understand physical properties and processes, and to identify research needs.

Just as it was necessary in the first section to describe sea ice at two scales--as a material and in the aggregate--this section is similarly organized. In addition, the mechanical properties of model and artificial ice are reviewed in a third section.

Material Properties of Sea Ice

The need to establish the mechanical properties of sea ice on the scale of interaction with large structures presents formidable difficulties. The scale is so large that it may not be possible to directly measure any of the desired properties until instrumented structures are designed, constructed, and operated for an extended time. A more practical approach to the problem is to use smaller scale tests to provide data from which the properties of large ice masses can be established through scaling relationships or mathematical models.

In general, the smaller the scale at which a particular type of test is performed, the greater the number of tests which can be run for a given time or funding level. Because of the large number of variables that affect the mechanical properties of sea ice, it is likely that functional relationships will be determined by laboratory or small-scale field experiments, and the resulting curves 'calibrated' to progressively larger scales through a relatively few, selected experimental programs using appropriately large samples.

Few experimental programs have involved samples up to the full thickness of a late winter ice sheet in the Arctic (AOGA, 1980; Croasdale, 1974; Vaudrey, 1977; Kry, 1975).[81,82,83,84] Therefore, most of the results discussed in the following paragraphs were drawn from small-scale laboratory or *in situ* beam tests. This discussion notes numerous problems associated with the organization and interpretation of these data which tend to limit their usefulness.

The general characteristics of first-year sea ice, in terms of salinity, crystal size and fabric variations, etc., were discussed in Section I. The range and scale of possible structural variations in multi-year ice is not known. However, considering the combinations of thermal and dynamic histories which can affect an ice mass that has survived one or more melt seasons, the range must be large. In addition, superimposed over these variations is a vertical temperature difference between the top and bottom of an ice mass which can exceed 40°C. Mechanical properties are dependent upon all of these variables to some degree. The strength of sea ice for any loading mode (i.e., compression, tension, shear, bending) is also highly dependent upon the rate at which stress is applied. For engineering applications, knowledge of the strength over several orders of magnitude of this rate (under confining pressures where applicable) is required. This corresponds to a range from ductile failure at low strength and rate to brittle failure at high strength and rate. The required data can be obtained from tests in constant stress-rate, constant strain-rate or constant stress (stress-rupture tests). However, there are problems of interpretation in correlating the results from different test types. The rate dependency also extends to other properties which will require the application of theories of visco-elasticity for interpretation.

Some factors that limit the usefulness of many laboratory studies of the mechanical properties of sea ice done in the past are:

1. The lack of standardization of procedures for sample selection, preparation, and testing makes it difficult to reconcile results from different test programs.

2. The importance of ice crystal shape and orientation, or, more broadly, the internal structure of the ice, to mechanical properties has only recently been emphasized.

3. A detailed classification of sea ice is lacking, and sample characteristics have not always been adequately described. Thus, apparently similar test programs can produce different results which cannot then be properly interpreted.

4. Strain measurements have often been made by monitoring platen displacement rather than sample strain. Similarly, constant strain-rate tests were usually done under conditions of constant platen speed, rather than through the use of a closed-loop feedback system based upon sample strain rate.

5. Grain (or crystal) size variations in natural sea ice have not been accommodated by adjusting sample volume to maintain a constant ratio of average grain size to sample volume. There may be some lower limit to the number of grains which must be included in a sample in order to give consistent results, but, as yet, this has not been established.

These difficulties are recognized, and are accommodated, to varying degrees, in recent and current work. Standard procedures for sample collection, handling, and testing have been suggested (IAHR, 1980).[85] However, the lack of a detailed classification of sea ice types and variations is still a problem, although those proposed for fresh ice by Michel and Ramseier (1971)[86] and Cherepanov (1974)[87] provide a good start. The problem is more acute for multi-year ice since the range of varieties that can occur has not been identified and classified.

It should be noted that most of the problems and pitfalls in testing sea ice are applicable to tests involving samples of any size. Therefore, the effect of natural variability, rate, etc., will be superimposed on the size effect. Finally, it is important to emphasize that no small laboratory sample can possibly include the range of variations of structure, temperature, and salinity gradients of a large ice sheet. Thus, the scaling problem is not simply a matter of compensating for a difference in size of two samples of the same material. Instead, mathematical development and studies of deformation and failure mechanisms may be required to fully establish a correlation. Yet, it is knowledge of the properties of ice sheets on the larger scale that is ultimately of concern for many engineering applications.

The problems outlined above can be recognized as resulting from several sources. The first, and perhaps the most formidable, is the natural variability of the material as it occurs in nature, including the properties of a typical ice sheet or ice mass, and the gradients imposed upon it by the environment. The lack of standardization in procedures makes each investigation essentially independent of others, so that it is difficult to correlate results between investigators. The study of the mechanical properties of sea ice is still rather young, so that several important topics such as the effects of grain size and orientation have received only minimal attention.

The mechanical properties of sea ice have been reviewed by Weeks and Assur (1967, 1969),[88,89] Doronin and Kheisin (1975),[90] and Schwarz and Weeks (1977).[91] The following discussions are largely based on these references.

Stress-Strain Laws for Sea Ice

Stress may be related to the state variables of strain, salinity, temperature, and time. In a given sample a viscoelastic description may be appropriate, where the strain and strain rate under load are dependent upon the magnitude of applied stress and the rate of stress application. Time-dependent effects contribute a significant part of the strain for loads applied over time scales that are important in engineering applications. Thus, while elastic or elastic-plastic analyses can be useful in predicting limiting, or instantaneous relationships, a complete description of the response of sea ice to applied stresses will depend upon the development of a comprehensive viscoelastic stress-strain law.

Few attempts have been made to formulate viscoelastic stress-strain laws for sea ice, particularly for non-linear cases. Understanding of the problem is rudimentary at best; non-linear viscoelastic stress-strain laws are not in general use for other materials, and the background required is possibly not widely distributed among the community of researchers and engineers who are concerned with sea ice. Only two published papers deal with attempts to interpret sea ice test data to yield viscoelastic properties; one for uniaxial compression and bending of small samples (Tabata, 1958)[92] and the other for the bearing capacity of ice sheets (Vaudrey, 1977).[93] The latter can probably be considered to be operational.

Because of the range of ice properties and environmental variables that can affect the deformational properties of sea ice, it is unlikely that generalized viscoelastic stress-strain laws will be available in the near future. However, studies aimed at developing such laws are clearly warranted for application in the longer term.

When time is omitted from the constitutive laws for sea ice, an elastic description of the properties is usually attempted. Measurements of elastic properties are divided by methodology into two categories, static and dynamic. The distinction is important because of the time-dependence of properties described in the previous section. In dynamic tests, rapid loading rates are applied by propagating elastic waves through the samples. The velocities of various phases are measured, and the elastic moduli are then calculated from the data, using the assumption that the ice is homogeneous and isotropic. With the high loading rate and low magnitude of the propagating stress, time-dependent effects are negligible. In static tests, loads are applied more slowly so that a contribution from time-dependent deformation mechanisms is to be anticipated. Calculation of the moduli is generally done via a linear stress-strain law in which the material is also assumed to be homogeneous and isotropic.

The available test data for the elastic properties of first-year sea ice modeled as an isotropic, homogeneous material, can be summarized by noting that Young's modulus* is the most studied of the elastic moduli in both the static and dynamic modes. Values from dynamic tests are reasonably consistent, but those from static tests show wide variation. The range of possible values over the full range of temperatures, salinities, and ice structure that could be encountered in nature, is yet to be determined for either case. Poisson's ratio** has been determined with good repeatibility from dynamic tests, and the results indicate little variation with temperature, salinity, and ice fabric. The shear modulus determinations from shear wave propagation velocity data are generally scattered and inconsistent. Neither Poisson's ratio nor the shear modulus have been measured by static test methods.

Few static test values exist for the elastic properties of multi-year ice, and these are not referenced to ice characteristics.

The existing results for creep and elastic properties are incomplete. Indeed, they pay no attention to the essentially non-isotropic and non-homogeneous characteristics of sea ice. These simplifications may be reasonable for applications that do not depend strongly on the deformation characteristics of ice prior to failure.

Strength of Sea Ice

Strength is defined as the maximum stress achieved in any test in which the sample is loaded to failure. Strength is a function of temperature, ice properties, and test parameters such as the rate of application of the stress, or the time that a particular load is maintained on a sample. For some applications, post-yield behavior (the ability of a sample to sustain a load after the peak stress is reached) is also of interest. In other cases, such as studies of load bearing capability, the objective is to determine the length of time that a load can safely be placed on an ice sheet before some critical stress or deformation is reached.

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*Young's modulus: The ratio of the stress in a material to the corresponding strain.

**Poisson's ratio: The ratio of transverse to longitudinal strain in a material under stress tension.

The strength of sea ice is of interest over the entire range from ductile failure under low constant stress or low rates of stress application to brittle failure under high loading rates. Considering the number of possible variations in temperature, ice properties, fabrics, loading modes, and other test parameters, it is clear that to define the strength experimentally will require a large number of tests. The problem is compounded by the absence of any failure criterion for sea ice with other than a narrow range of application.

Many studies of uniaxial compressive strength have been reported in the literature, but, to date, tests have not been run over the full range of temperatures and salinities encountered in nature. A wide variety of test techniques and lack of reported test conditions frequently make comparison difficult. Orientation effects in the horizontal plane have not been thoroughly considered, and a controversy exists over the possibility that the strength decreases at high loading rates in the range of brittle failure. No published, systematic studies have appeared on the strength of multi-year ice, although some relevant data are scattered in publications on sea ice in general. No studies have been reported in the literature on the effect of biaxial or triaxial confining pressures on the strength of sea ice.

Most reported values of tensile strength are derived from tests in bending, or indirect tension. All require an assumption about the material properties, in the form of a stress-strain law, in order to calculate the strength. There are also questions regarding whether such indirect testing methods can give meaningful results for a material with the structure and tensile strength/compressive strength ratio of sea ice.

Direct tension tests provide the most satisfactory, and most difficult, measurement technique. However, only two such studies have been reported in the literature. In one of these, the samples were smaller than the crystal size, and laboratory grown ice was used for the other. The results suggest that load rate effects may not be as important as in the case of compressive strength measurements.

There have been few studies of the shear strength of sea ice. Many tests that were reported as shear tests were actually done in mixed mode loading. The results indicate a strong dependence on loading rate, but there are few data with which to evaluate this. The dependence of shear strength on temperature, salinity, structure, and other variables is even less certain.

Flexural strength, or the modulus of rupture, is not a material property, but it is an important parameter that serves as a useful index and is used to design offshore structures. Measurements of this parameter have been made in small-scale laboratory tests and on large, _in situ_ beams with linear dimensions on the order of several meters and involving the full thickness of an ice sheet. Both simply supported and cantilevered beams have been used in the experiments, and, in general, differences in results have not been reconciled.

Brine volume effects at constant loading rates seem consistent for cantilever beams, but the rate effect is not known. As an example, in situ cantilever beam tests indicate a strong dependence on rate. However, in one investigation, calculations which eliminate the inertial force associated with the displacement of water during the bending remove this rate dependency. In general, test results are not reproducible and consistent, and problems remain involving size effects and mechanisms. In addition, as with other tests, procedures have not been standardized, so that correlation of results between investigators is difficult.

As a final product, it would be reasonable to test hypotheses for sea ice strength and fix an appropriate model which can be determined from a uniaxial test and the state properties. In reality, the interest is in two dimensional, plane stress results. A test program on biaxially loaded specimens could lead to the substantiation of an ice failure model, or at least aid in its construction. The effects of loading rate are critical; for the battering of ice against a vessel, the fracture character would be different than for effect of the slow loading process of ice impinging on a fixed structure. A test program should give information on the different results for brittle and ductile failure.

Friction and Adhesion of Sea Ice

Several recent studies are available which give a rather large range of values for both the static and kinetic friction of sea ice on various surfaces. As an example, reported values of the coefficient of static friction of sea ice on steel range from 0.25 to 0.70. Temperature effects are thought to be negligible unless the ice freezes to the surface, in which case adhesion enters the problem. Values of the coefficient of sliding friction are generally lower than those for static friction by a factor of about one to ten. Systematic studies of frictional properties, as a function of the physical properties of the ice and temperature, have not been done. At present, results scatter over a wide range and are probably not useful for more than rough estimates. Few detailed studies of adhesion of sea ice to various materials have been done.

Thermal Properties of Sea Ice

A knowledge of the thermal properties of sea ice is needed for many engineering problems dealing with the growth, thickness, and temperature of natural and man-made sea ice. It is often desirable to predict, or hindcast, the thickness of an ice sheet where measured ice thickness data are lacking or difficult to obtain (Mettler and Stehle, 1965; Lewis, 1967).[94,95] The ice thickness has an important influence on the bearing capacity of the ice (Kerr, 1975)[96] and loads of a moving ice sheet on offshore structures (Croasdale, 1975; Ralston, 1978).[97,98] It is also useful to be able to predict the ice temperature as most of the mechanical properties of sea ice are strongly temperature dependent (Schwarz and Weeks, 1977).[99] Other applications of sea ice thermal properties include evaluating the thermodynamic influence of the arctic pack on global meteorology (Maykut and Untersteiner, 1971);[100] thermal ice thrust on marine structures and predicting the growth rate and temperature of artificial sea ice constructed by flooding (Adams et. al., 1960; Cox, 1979).[101,102]

In modeling the temperature or growth of sea ice we are concerned with the sea ice specific heat, thermal conductivity, density, and latent heat. In addition to these parameters, the coefficient of thermal expansion is used to estimate thermal ice thrust. All these parameters are strongly dependent on the sea ice salinity, temperature, and air volume, particularly near the melting point. The ice thermal conductivity also depends on geometric distribution of brine and air cavities in the ice.

The specific heat, thermal conductivity, density, and latent heat of sea ice have been well defined by the efforts of Anderson (1960),[103] Schwerdtferger (1963),[104] Ono (1967, 1975),[105,106] and Dixit and Pounder (1975).[107] The variation of these parameters with ice salinity, temperature, and air volume have been calculated based on the thermal properties and distribution of the different phases in the ice (ice, brine, and air) and phase relations. Calculated and experimental values of the specific heat and thermal conductivity are in good agreement. A review and comparison of the findings of the various investigators can be found in Schwarz and Weeks (1977).[108]

Cox and Weeks (1975)[109] have also calculated the thermal properties of NaCl ice, and a review of the thermal properties of fresh water ice, including the coefficient of thermal expansion, is given in Drouin and Michel (1974).[110]

The only available work on the coefficient of thermal expansion of sea ice was performed by Anderson (1960).[111] Anderson calculated the coefficient of expansion from theoretical phase relations. His calculations indicate that the coefficient does not vary linearly with temperature as in most materials. Instead, the coefficient varies over several orders of magnitude in a non-linear fashion with temperature and has a major discontinuity at the NaCl $2H_2O$ eutectic. Depending on the ice temperature, the coefficient can be negative (expansion) or positive (contraction). Pettersson's coefficient of thermal expansion data shows this non-linear behavior without a discontinuity at the NaCl $2H_2O$ eutectic (quoted in Malmgren, 1927).[112] Thermal strains have been measured on ice blocks by Ono (1976) in the field.[113]

Except for the thermal expansion coefficient, the basic thermal properties of sea ice have been well defined. There is some uncertainty as to the importance of thermal ice thrust on offshore arctic structures. However, ice loads due to thermal expansion of the ice are probably less than those associated with wind-induced motions or pack ice forces. Similarly, the ice movement rates or ice strain rates associated with thermal expansion are probably lower.

Properties of Aggregate Masses of Sea Ice

Sheets

Sheet ice is considered to be of unlimited extent and of more or less uniform thickness. The initial state of in-plane strain depends on the air and sea state at a distance and, although these causative features are not a part of the panel's study, the resulting strain state is critical in a discussion of ice sheets. As noted earlier, the fracture of these sheets is significant in maritime ice breaking and in the interaction of the ice sheet with fixed structures. After fracture, the fragments can ride up on top of each other and on the sheet, as a genesis to ridge building and as an augmentation of the gravity loads on ships and structures. The comments here deal with the failure, both in-plane and flexural, of such sheets, the pressure distributions of sheets on ships and structures, the pile-up that occurs after fracture, and the bearing capacity of ice sheets. From a practical viewpoint, it is essential that the ice fail before the ship or structure does, that the pressures on the structures do not cause failure, and that the subsequent pile-up of ice does not constrain the use of the ship or structure.

The information needed concerns failure modes of the ice, pressure of ice on ships and structures, and the kinematics of fractured ice sheets. Obtaining this information is a conventional problem in mechanics. The solution is of critical importance for safe engineering in the Arctic. Failure modes may be by bending or by in-plane separation. Causes can be associated with either the large change of momentum of a moving vessel striking a sheet or the slower occurrence when the existing strain state interacts with a fixed structure. The large change of momentum featured in collision of ship structure with ice results in a rapid failure, which can be characterized as brittle fracture. The case of the slow interaction between a structure and ice produces creep strains in the ice prior to failure. The failure is markedly different from the striking problem and involves ductility. It is termed a creep fracture.

The pressure of the ice on bodies is clearly of importance in designing ship hulls and for stability calculations of fixed structures. At present, ship plating is designed for specified pressures which vary by 100 percent. However, it appears that failures seldom occur. This would suggest that the effect of ice pressure on ship plating is little understood. This is the local pressure problem.

Of interest also is the integrated pressure or force problem. Here a measure of the ice thrust against a structure is required. The combined problem requires an understanding of the stochastic variation of pressure of the ice and the statistics which provide average measures and forces. Finally, the pile-up of fractured ice ensures another loading system on structures. Here the fragment geometry must be understood as well as the past fracturing kinematics.

The problem of the bearing capacity of ice sheets is of importance when natural or man-made sea ice is used as a load bearing engineering structure. Examples of this type of use are: ice roads, ridges, runways, and aircraft parking aprons. The bearing capacity of floating ice sheets has been studied extensively and a summary of these studies has been done by Kerr (1975).[114] As the engineering operations on floating ice sheets increase so will the need for proven design criteria for the bearing capacity of ice sheets. Large-scale tests to determine the criteria of the bearing capacity are required.

From an analytical viewpoint the theory of plates is a well understood subject which can be used with confidence. Finite element procedures allow a range of material properties to be included in the analysis. In this way, the practicality of the analysis has been enlarged. Nevertheless, the material parameters, boundary conditions, and loading functions are difficult to include in the analysis.

The main thrust of research work should be associated with identifying gross parameters for plates. This means that, if small scale tests are used to determine material properties, there must be adequate experimental work to show the correlation with results on specimens of full sheet ice thickness. The scaling problem has to be solved for adequate use of analytical schemes. Up to now, the extensive use of dimensional analysis has not been employed. This approach to seeking scaling relationships has been successful in other areas. In general, there are no success stories about integrating microproperties to obtain macroproperties. In order to avoid a repetition of failure, the scaling suggested here is from micro to gross, where the scaling ratio is an order of magnitude. The dimensional analysis approach should be valid and usable in determining the different scaling for different failure modes. This is particularly important in separating scaling for shear and bending.

Ridges

Although there is general agreement that ridges and ridging are factors that must be considered in offshore design, there are still many aspects of these features that are poorly understood. To be specific, although not strictly a subject within ice mechanics, there is a need to develop improved statistical models for predicting rare, large ridges of the type that might be used in setting a design. There is also a need for data on the lateral variation in the thicknesses of ridges. P-ridge data (Hibler and Ackley, 1973)[115] suggest that autocorrelations of sail height measured along ridges are zero at distances of more than approximately 25 meters, and also that "holes" through ridges are randomly placed along the ridge. It is the panel's impression that the sail heights of s-ridges are more laterally consistent than this although there are no pertinent measurements. These matters are, of course, quite important in the design of large structures as they provide information on the possible uniformity of the loading along the structure. Also any additional information on the degree of correlation between sail heights and keel depths would contribute to our ability to confidently estimate the variations in ice thickness caused by ridging.

An important subject where more field observations are required is that of the bulk mechanical properties of ridges and, in particular, the keels of ridges. Here we refer not only to the state of the ice in the blocks comprising ridges but also, in particular, to the degree of bonding between blocks as it affects the overall strength of the ridge. Of special interest is the degree of bonding in the keels of thick multi-year ridges. Although it does appear to be true that the upper portions of many multi-year ridges are massive and void-free (Kovacs et al., 1973),[116] there are still questions about the degree of bonding in the lower portions of the keels of the larger of these types of ridges. Also more information on the shapes of multi-year ridge keels would be useful. Such data would contribute directly to the ability to estimate both the point and distributed loads that would be expected when such ice masses move against offshore structures.

It would also be highly useful to attempt to extend and calibrate the Parmeter and Coon (1972)[117] model for ridging. The reasons for this are twofold. First, the failure of ice against some structures, in particular against gravel islands, is largely due to ice-ice interactions and is very similar to grounded ridging. Also it is quite possible that ridging within the nearby pack serves as the limiting factor that controls the maximum distributed force that will be exerted against an offshore structure. Efforts in theoretical ridge modeling should be supplemented with expanded laboratory studies of the ridging process via the use of model basins and a variety of test ices (Lewis and Croasdale, 1978).[118] One problem that should be explored further, using a combination of the above techniques, is the mechanical difference between grounded and non-grounded ridges. As is evident from the work of Parmeter and Coon (1972)[119] and Kovacs and Sodhi (1980),[120] there are many mechanical similarities between offshore ridges and near shore pile-ups and overrides.

Finally it could be highly useful to utilize icebreakers in the study of the gross mechanical characteristics of ridges since there are considerable similarities between the nature of ship-induced ice breaking and the breaking of drifting ice around fixed structures (Gerwick and Karp, 1979).[121]

Rubble Fields

Ice rubble fields are accumulations of broken, first-year ice blocks, with greater width/thickness ratios than pressure ridges. They may be grounded or floating. Grounded rubble fields have been observed to form along the coast, on shoals, against offshore islands and structures, and as isolated accumulations in relatively undeformed fast ice. Floating rubble accumulations are generally found in shear areas between the dynamic pack ice and relatively stable landfast ice, and in areas of strong ice convergence.

Newly formed rubble accumulations are unconsolidated aggregates with properties which may be similar to granular materials. After formation, the ice blocks may freeze together, including the water-filled spaces between blocks, to form a consolidated ice mass.

Properties of interest include spatial and temporal statistics on rubble geometry (length, width, and thickness), block size distribution, void ratio, and the degree of consolidation of the rubble mass. Ice temperature and salinity profiles through the rubble should also be obtained to better understand the consolidation process and estimate the overall rubble mechanical properties. Mechanical properties of interest include the shear and compressive strengths of both unconsolidated and consolidated rubble masses. In areas of dynamic ice movement, information is needed on the motion of large, consolidated rubble fields and piles to assess the risk of rubble-structure interaction.

In many cases, rubble fields and pile-ups appear to be lateral growth extensions of a pressure or shear ridge. From work done by Weeks et. al., (1971),[122] Kovacs and Mellor (1974),[123] Rigby and Hanson (1976),[124] and other pressure ridge studies cited in the previous sub-section, some idea of the physical nature of large rubble masses can be obtained. Some detailed information is available on the characteristics of pile-ups around structures (Kry, 1977; Ralston, 1979)[125,126] and along the Arctic coast (Kovacs and Sodhi, 1979).[127] A few detailed investigations have also been performed by the petroleum industry on isolated rubble piles in the Northern Bering Sea and first-year ice features in the Beaufort Sea. Finally, review articles have been written on the distribution of large rubble fields (shear or stamukhi zones) in the Southern Beaufort Sea (Kovacs and Mellor, 1974;[128] Kovacs, 1976;[129] Reimnitz et al., 1977;[130] and Stringer, 1979).[131]

Small scale laboratory tests have been performed to obtain a preliminary understanding of the mechanical properties of unconsolidated rubble. Shear and compressive strength studies have been conducted by Prodanovic (1979),[132] Tatinclaux and Cheng (1978),[133] and Keinonen and Nyman (1978).[134]

Unfortunately, the results from the shear strength tests differ from study to study. This can, in part, be attributed to differences in test apparatus, and to variations in the test material and conditions. However, despite these differences, the ice rubble appears to behave like other granular materials. In a study by Prodanovic (1979),[135] cohesion and friction angles determined from direct shear box tests, rubble-cylinder interaction model tests, and plastic limit analyses were found to agree. The rubble shear strength seems to be independent of strain rate and to increase with ice block thickness. More tests need to be conducted to confirm these results and evaluate scale effects.

There are insufficient data to comment on the compressive strength of ice rubble. No studies have been performed on the mechanical properties of consolidated, or partially consolidated rubble, and techniques are not available to predict design-case rubble geometries around offshore structures from ice movement data. *In situ* ice stress measurements, both inside and outside the rubble zone, are needed to confirm theoretical and model test results.

Fragmented Ice Covers

A fragmented ice cover is a loose accumulation of floating ice pieces in which the ice piece dimensions are small enough so that the pieces do not act as infinite plates. With regard to many offshore structural design considerations, fragmented ice covers tend to represent an operational condition rather than a design event. For example, a 30 percent ice coverage of 6 m diameter floes in the Beaufort Sea would not be a significant factor in the stability of a gravel island, but it would affect the operation of a floating dredge pipeline that could be used to construct a gravel island.

Fragmented ice covers are created in the Beaufort Sea by the breakup process that occurs in early July. Summer ice invasions may also contain floe sizes sufficiently small to be considered fragmented ice. The southern ice edge in the Bering Sea is an area of fragmented ice that results from wave action on the southerly advancing ice edge.

The data of interest for assessing the effects of fragmented ice covers include the physical size and mechanical properties of individual ice pieces and the large-scale mechanical response of collections of individual pieces that act as an aggregate. Local ice loads are created by individual fragment collisions. The magnitude of these loads can be limited by the local crushing of fragments or other failure modes, such as ice floe splitting, that depend on the full-thickness mechanical properties of individual ice pieces.

The aggregate properties of fragmented ice covers limit the environmental driving force that can be transferred through a fragmented ice cover. The behavior of individual pieces, which may buckle when subjected to in-plane loads, plays an important role in determining aggregate properties (Coon, 1972).[136] For a given ice coverage and distribution of floe sizes in a fragmented ice cover, the loads developed by the interaction of the largest floes with an offshore structure may be limited by the magnitude of the environmental driving force that can be transferred through the fragmented ice cover to the larger floes. Thus, the aggregate ice properties of interest include a material strength model and the evaluation of the aggregate material strength parameters, which depend on the ice piece thickness and size distribution and the rate at which the deformation processes occur.

The properties of individual ice pieces are essentially the properties covered earlier in the discussion of properties of sea ice as a material. However, the temperature of such covers are usually relatively warm since that most fragmented ice covers occur in relatively warm thermal regimes and are associated with ice temperatures near the water temperatures.

Since there is not a clear distinction between the aggregrate properties of fragmented ice covers and unconsolidated ice rubble, some of the model basin test data (Prodanovic, 1979; Keinonen and Nyman, 1978)[137,138] obtained with various materials suggest that the aggregate behavior of a fragmented ice cover can be described by material models that are similar to those used for other granular materials.

Field studies of fragmented ice covers have been conducted to determine the floe size distribution by means of aerial photography (Deily, 1979)[139] and to determine the effects of ocean wave attenuation near the ice edge (Wadhams and Squire, 1980).[140] Techniques for the creation of a fragmented ice cover have been explored by Canmar in support of floating drilling operations in the presence of ice in the Canadian Beaufort Sea. O'Rourke (1979)[141] reports that analyses and model tests were conducted which indicated that a drill ship could operate in sufficiently well broken ice, 0.6 to 0.9 meters thick, without reaching the limit of the mooring line tensions. These results led to a full-scale field trial in which a Canadian icebreaker and supply vessels were used to break moving ice sheets near a drilling vessel. The trial was successful and showed that the limitations of the system were essentially the ability of the icebreaker support vessels to break the moving ice into sufficiently small pieces prior to its reaching the vessel.

Industry is continuing to collect environmental data in the form of remote imagery and ice movement measurements that add to our knowledge of fragmented ice covers. It is also reasonable to assume that model tests of operational procedures that are affected by fragmented ice covers will be conducted as needed. The field experience developed by Canmar's floating drilling activities should continue to provide additional insight into the full-scale behavior of fragmented ice covers.

There is room for continued refinement of present knowledge of the mechanical behavior of fragmented ice covers through the analysis of existing data. Perhaps the most important application would be the ability to quantify the limits on the environmental driving force that could be applied to an offshore structure by a fragmented ice cover. Presumably, these limits would depend on the parameters (thickness, floe size distribution, etc.) that define the fragmented ice cover.

Unconsolidated Brash and Frazil Ice

These forms of sea ice are discussed here at length in this report because of the relative paucity of documentation concerning these topics.

Free-floating crystals of ice in the water column are called frazil. These crystals floc and freeze together to form frazil ice. In contrast to frazil ice, which is the result of new crystal growth, brash ice is an accumulation of floating ice composed of fragments not more than two meters across that are formed from the wreckage of other forms of ice.

Frazil is known to form in turbulent streams and may comprise a significant component of the ice cover of some rivers (Ashton, 1980).[142]

Frazil in sea water is believed to form in two ways. In the first case, frazil is known to form at the edge of advancing ice covers and in open leads in the pack at locations where wave induced turbulence causes newly formed ice crystals and supercooled water to be swept beneath the water surface and distributed throughout the upper portion of the water column. In the second case, cold dense brine formed during the formation of sea ice plummets downward into the underlying liquid seeking to achieve a stable density distribution. As this brine is at temperatures appreciably below the freezing temperature of bulk sea water, ice crystal nuclei are swept down with the brine and frazil crystals are formed. Such crystals ultimately float to the surface where they are incorporated into the base of the growing ice sheet. These two processes are, of course, not mutually exclusive. The resulting frazil ice is commonly equigranular with a grain size of less than 2 mm and a random C-axis orientation. Such ice has commonly been considered to be interesting (at least to crystallographers) but relatively unimportant in the volumetric sense. In recent work along the Alaskan coast, Weeks and Gow (1979)[143] found frazil ice in significant thicknesses (> 50 cm) at less than 5 percent of the sites visited, although the upper few centimeters of ice at many locations were of this type. However, unpublished observations by Ackley and Gow[144] in the Weddell Sea show that there frazil ice is a major component of the ice cover (approximately 50 percent) with thick frazil layers occurring at numerous locations (in a vertical sense) within the ice. Further field sampling to determine the presence of frazil and research on the reasons, therefore, are needed.

Whatever the ultimate volumetric importance of the frazil ice component of sea ice, there is at present no information available on the mechanical properties of this material. To speculate on the results of such future studies, one would guess that frazil saline ice would show a linear decrease in strength with increasing brine volume since the brine pockets are presumably randomly distributed throughout the ice. It is assumed that the strength value at zero brine volume would be close to that of frazil ice from rivers (a material that has been studied; Ramseier, 1971).[145]

One reason that frazil ice is of concern to engineers is because frazil is capable of clogging water intakes and other piping systems that are open to the arctic marine environment. This is because, in their early growth stages, frazil crystals show a strong tendency to adhere to each other and to other available surfaces.

Brash ice is derived from the wreckage of other forms of ice. This wreckage process consists of the continual grinding of floes together during periods of pronounced differential ice motion. There are, to the panel's knowledge, no studies of the relative percentage of pack ice that can be classified as brash ice. However it is presumed to be at least several percent, particularly in the spring, summer, and early fall. This is particularly true in applications relating to shipping since ships prefer to transit along floe boundaries, areas where brash ice accumulates.

The mechanical properties of brash ice have not received much attention. One problem is that when brash ice containing fragments of up to two meters is of investigative interest, the sample size would have to be very large in order to incorporate an adequate representation of such fragments. As brash ice is, by definition, produced by cataclastic interactions between floes, it is reasonable to assume that its grain structure would be fairly equigranular resulting in a reasonably isotropic material. In fact, brash ice probably has a structure presumably somewhat similar, in a gross way, to frazil ice but with a much, much larger variation in the range of effective grain sizes. In fact, one would expect frazil ice to actually comprise an appreciable percentage of brash ice. A reasonable difference between brash and pure frazil is that the larger grain sizes commonly present in brash result in an absence of the spontaneous inter-particle cohesion that is characteristic of frazil. Also because brash ice is an ice-sea water mixture its temperature is roughly constant at the freezing temperature of the ambient sea water.

There is only a limited amount of information currently available on the mechanical properties of brash ice (see the review given by Mellor, 1980).[146] As most brash ice problems are concerned with large deformation and yielding, it is natural to think of the material in terms of a yield criterion such as that used for other granular materials. Usually a linear criterion has proven to be a satisfactory approximation as the bulk stresses are commonly small. If the bulk stresses were to become large, this linear relation would presumably break down tending toward a limit determined by the strength of the ice particles themselves. For specific studies of brash properties, one should refer to the work of Cheng and Tatinclaux (1977)[147] and Tatinclaux et al. (1977)[148] [experiments on fresh water brash ice] plus the work of Keinonen and Nyman (1978)[149] and Prodanovic (1979)[150] [experiments on model saline ice]. Values for ϕ , the friction angle, are surprisingly high as compared with typical values for dry granular solids. There is also a yet unexplained decrease in compressive resistance with pushing speed. Tests over a wide range of size gradations of the ice fragments and degree of packing also have yet to be carried out. There is also no indication that allowance was made in these tests that have been made for the contribution to the normal stress induced by the gravity body forces. Neglect of such forces makes the properties of a brash ice layer dependent on the thickness of the layer. Since such "corrections" are always somewhat uncertain and since our interest is normally in the properties of thick brash layers, it is particularly important that data be collected directly on such ice masses.

Mechanical Properties of Model and Artificial Ice

Model Ice

The term model ice refers to materials that are used in laboratory investigations of sea ice mechanics for engineering design or research purposes. These may include ice, doped ice, or other materials such as paraffin. The subject of model ice is treated in some detail here because the technique provides a low-cost means (compared to field tests) of acquiring large ice structure data. Further, this report offers an opportunity to provide a thorough discussion of a topic that has not been so treated in the engineering literature.

Scale model testing is a useful technique for gaining insight into the mechanics of sea ice and the effect of ice forces on large structures. A small scale replica of the desired structure is constructed and subjected to conditions that simulate those that are likely to be encountered on the full scale structure. Measurements, such as forces or displacements made on the model structure, are then scaled to full size using suitable equations (see Michel (1978)[151] for a compact introduction to the modeling of ice related problems).

The main problem in successfully using such an approach is largely one of correctly scaling the properties of the "ice" in the model. Ideally, one would like simultaneously to obtain geometric, kinematic, and dynamic similitude in scaling. In fact, this ideal has rarely, if ever, been achieved. Common practice in such problems has been to scale by Froude's Law. In this case, the geometry values as well as the ice strength σ_f are reduced by λ and the velocity by λ where λ is the scale factor. Investigators have found that the necessary σ_f reduction could be accomplished by using high salinity (sea or NaCl) ice as the model ice. For some problems, such model ice has proven quite adequate.

For analysis of problems of distorted ice models, including scaling, see Michel (1978)[152] and Lewis, Kotras, and Etzel (1977).[153]

However, as most ice problems involve the rupture of ice, which in turn is a function of its material properties, it is usually necessary to scale both the elasticity (E) as well as strength (σ_f)

by the same factor. Such simultaneous scaling of σ_f and E is difficult using saline ice as σ_f and E are different functions of the brine volume (see Weeks and Assur, 1967),[154] whereas the intent is to produce a model ice with the same E/σ_f ratio as the real ice. Current practice (Schwarz, 1977)[155] is to warm the model ice to near-melting temperatures just prior to testing, thereby raising the E/σ_f ratio and to also utilize model scales that are less than a one to 20 ratio.

Although it is possible, via such procedures, to obtain model E/σ_f ratios that are similar to those of the prototype, the process is, at best, an experimental bother. Therefore, considerable thought has been given to alternate procedures for handling or for producing model ice. Here two main approaches have been taken. The first (Timco, 1979, 1980)[156,157] has looked for improved dopants for modifying the properties of thin ice skims in order to achieve a proper E/σ_f ratio. At the present, the most promising dopant appears to be urea (carbamide), and some test basins have converted to this new ice as improved E/σ_f ratios are definitely possible. Initial tests are promising; however, it still is necessary to perform the tests at near melting temperatures in order to achieve the desired ratios.

Just how different dopants work is poorly understood. In saline ice, the amount of salt going into solid solution in the ice phase is believed to be negligible, and the property variations are achieved by variations in the brine volume ν. In urea ice, the volume of urea solution varies in a similar manner. In addition, it is quite probable that part of the urea in solution hydrolyzes producing the NH^{+4} (ammonium) ion which in turn is capable of going into solid solution in ice, resulting in large changes in its elastic properties. There are also major differences in the crystal structures of ice sheets formed using different dopants. In a way, this complexity is promising since, if these different effects are understood, it should be possible to fine-tune model ice to the requirements of specific problems. Research currently is a long way from this goal.

There are several drawbacks to the use of doped ices as a model media. First, there are invariably large ice property variations across the model ice sheets as the result of grain size and crystal orientation variations. These effects are hard to control and poorly understood. Admittedly artificial seeding of the model ice can help here and is extensively used. Nevertheless, one must deal with, at least, a two layered medium that also presumably shows appreciable lateral variations. The second problem is caused by having to test at near melting temperatures in order to achieve the necessary E/σ_f ratios. At these temperatures, small temperature variations cause large ice property changes making it again difficult to produce an ice sheet with uniform characteristics and also difficult to maintain constant properties during periods of more than a few minutes. In short, although urea ice makes improved E/σ_f ratios possible, many of the difficulties encountered in working with saline ice are still present.

Another approach to avoiding such difficulties is by the use of materials other than ice as the model substance. For instance, materials such as wood, polyethylene, and paraffin can be used to simulate ice floes. The problem is that although the density and size of these materials can be adjusted adequately in the model material, such materials do not simulate the mechanical properties of the ice. Therefore, such materials are only useful in cases where the ice floes react as discrete rigid bodies and cannot be used in problems where the mechanical properties of the ice cover are of importance. The primary exception to this statement is the material MOD-ICE developed by Michel (Kotras et al., 1977).[158] The composition of this synthetic material, composed of five components, is varied in order to scale approximately the flexural and crushing strength, elastic modulus, density, and roughness. The advantages are that MOD-ICE can be used at ambient temperatures and the model sheet is stable over a period of days, allowing unhurried testing, and is also presumably homogeneous. The friction coefficient is higher than that for natural ice (a factor that can be compensated by choosing a proper material for the structure being tested). The recipe is not publicly available information. This has limited the use of this material and kept its characteristics from being studied by other investigators.

It is also the panel's impression that, at least when doped ice is used, the pressures of rapidly completing the mechanical characterization of the material coupled with the general problems of performing tests on thin ice sheets causes the quality of these tests to be below those of similar procedures applied to thicker natural ice covers. The difficulty is that small changes, observed on the model resulting from testing procedures, can transform into large differences when applied to the prototype.

The litany of problems mentioned above might lead one to the conclusion that the modeling of ice problems has been of little use to the engineering community. This is definitely not the case. Modeling is a highly useful way of approaching many different problems. The point is that there is every reason to believe that additional research in this area should result in appreciable improvements in ice modeling techniques, flexibility in achieving appropriate scaling, and overall confidence in the results.

Artificial Sea Ice

Artificial sea ice comprises the preparation of reasonably thick sheets of ice in the laboratory for use as a test material in ice mechanics programs. This general problem has been discussed by Weeks and Cox (1974)[159] and by Dykins (1967, 1971)[160,161] and such procedures have proven to be quite useful. However, there still are no specific studies of the differencies, if any, between the mechanical properties of such ice and of natural sea ice.

A knowledge of the mechanical properties of artificial sea ice is needed to develop better ice construction techniques and design ice structures.

Most of the work on the mechanical properties of artificial sea ice has been performed by the Naval Civil Engineering Laboratory during the Point Barrow Trials (Dykins, 1962; and Dykins and Funai, 1962)[162,163] and during Project Sea Way (Kingery et al., 1962).[164] Data was obtained on the unconfined compressive strength and ring-tensile strength of confined-flooded ice and flooded-snow ice. Only ring tensile tests were conducted on free-flooded ice and ice-aggregate-fill.

More recently, data on the mechanical properties of man-made sea ice have been obtained by industry in support of various arctic petroleum activities (ice roads, floating ice platforms, and grounded ice islands). These data are proprietary and may be purchased through AGOA or APOA for private use.

Due to limited testing and the inhomogeneity of man-made ice, little is known about the effects of loading rate, confinement, and structure on its mechanical properties. Data from good tensile and shear strength tests are not available in the open literature. Despite this lack of understanding and paucity of data, it appears that sufficient information exists to satisfy the engineering requirements for the design and construction of ice roads, bridges, runways, and floating ice platforms. In these applications, the mechanical properties of the surrounding natural ice sheet are important.

SECTION IV
GOVERNMENT AND INDUSTRY ACTIVITY IN SEA ICE RESEARCH

Government

The federal government has direct interests and responsibilities in fostering investigations into the physical phenomena of ice mechanics and in enhancing knowledge and experience to support its regulatory role in arctic offshore development. Offshore activity in the Arctic has begun and is accelerating while faced with a number of new, largely ice-related, engineering problems requiring unique solutions. This contrasts sharply with development in the Gulf of Mexico which occurred relatively slowly and under less stringent regulatory conditions.

The level of activity in government supported and in-house sea ice mechanics research is modest; possibly no more than six to eight full-time equivalent scientists are active. This estimate, and the observation regarding the level of privately funded activity, were made by the panel members on the basis of their direct involvement in a cross-section of public and private research in the area, review of publications, and review of information provided by the government agencies supporting this study.

In its review of government activity in sea ice mechanics research, the panel noted that projects have involved several departments and agencies--the departments of Interior, Navy, Army, Transportation (Coast Guard), the National Oceanic and Atmospheric Administration, and the National Science Foundation. Although it has no research activity in this area, the Department of Energy (DOE) has fundamental interest in the nation's ability to develop the arctic offshore resources in a safe and timely manner; thus an understanding of the forces and risks imposed by sea ice on structures and operations could be of value to DOE as well.

Of the above government agencies only the Navy and the Army Cold Regions Research and Engineering Laboratory (USA CRREL) have the personnel and laboratory facilities to undertake a portion or all of the research in mechanics identified in this report. The Navy recently has not pursued such research on a continuous basis and has focused on mission-related investigations in those projects that have been undertaken; they have supported projects at universities occasionally. The Navy has coordinated such planning with the Corps of Engineers through formal Department of Defense review processes. The U.S. Army Cold Regions Research and Engineering Laboratory is the major U.S. government organization with an experienced staff with interests in this technology and has specialized equipment (26 cold rooms, a test model basin and modeling facility, and specialized library) for laboratory and field research in sea ice mechanics.

The Army's civil works mission has objectives in ice research common to the interests of other agencies. CRREL has provided personnel and field support for U.S. Geological Survey (USGS) arctic research and Coast Guard sponsored in situ studies in ice breaking.

The USGS has undertaken arctic geotechnical research but does not have specific expertise in sea ice mechanics, nor does it have associated laboratory facilities. The need to acquire knowledge in ice mechanics, either directly or via cooperative efforts, is a function of the USGS' mission as has been evidenced by its recurring support of research at CRREL.

During recent years, research support has been provided by the National Science Foundation (NSF) through its grants in response to unsolicited proposals for sea ice mechanics research, in the same manner as it supports research in other areas; NSF has no in-house research capability.

The National Oceanic and Atmospheric Administration (NOAA) has not undertaken research in sea ice mechanics of the character discussed in this report and has no capability to do so. However, NOAA administers research related to sea ice mechanics investigation through the Outer Continental Shelf Environmental Assessment Project (OCSEAP) funded by the Bureau of Land Management. The thrust of this program is to assist in resolution of environmental problems.

The other active public organizations in the United States, with a history of studies in sea ice mechanics, are the universities of Alaska and Washington. These latter organizations have focused on field programs and theoretical work and do not possess major experimental facilities.

In summary, the majority of government in-house facilities and a number of the research personnel that could undertake the investigations the panel has described are at USA CRREL. There is also a small pool of university research scientists; however, university facilities are more limited. Outside of Army civil mission activity, however, the only on-going sponsorship of government work in ice mechanics (and for sea ice mechanics to a lesser extent) is provided by NSF. At present, no single agency provides a government-wide focus in sea ice mechanics.

Industry

The panel estimates the level of industry activity in sea ice mechanics to be, at least, an order of magnitude greater than within the public sector. A number of sea ice research projects are supported by industry, and non-proprietary research results are disseminated by the Alaskan Oil and Gas Association (AOGA) for the Alaskan Arctic and by the Arctic Petroleum Operators Association (APOA) for the Canadian Arctic. The industry reports vary in the character of review they have received; some are company documents which have been reviewed only within the issuing organization, others have had a broader peer review treatment. Table IV-1 gives the addresses of these organizations as well as a listing of publications and sources where information on sea ice mechanics, including industry reports, can usually be found.

Many industry studies are actually carried out by contractors. A large number of organizations have participated in such work. One of these organizations, Arctec Incorporated, in fact, operates the only private-sector test model basin used for sea ice studies in the United States. There is usually a several year proprietary hold on release of the majority of industry sponsored research. However, it is possible for the government or private organizations to purchase the proprietary results of these studies.

Information and Education

Finally, two additional facts should be mentioned regarding information sources and education in this subject. There is no adequate textbook available that broadly treats the subject of sea ice mechanics. In addition, the panel has searched but not identified any courses that treat sea ice mechanics completely. Anyone wishing to build a capability in sea ice mechanics must find appropriate material, which is not a trivial task, and train him- or herself. This situation may change as universities are increasingly sensitized to the special engineering needs of land and sea frontier development.

TABLE IV-1

Sources of Information on Ice Mechanics

Symposia:

Port and Ocean Engineering under Arctic Conditions (POAC)

1971 The Norwegian Institute of Technology, Trondheim, Norway

1973 The University of Iceland, Reykjavik, Iceland

1975 The University of Alaska, Fairbanks, Alaska, USA

1977 The Memorial University of Newfoundland, St. John's, Newfoundland, Canada

1979 The Norwegian Institute of Technology, Trondheim, Norway

International Association for Hydraulic Research (IAHR)

1970 Symposium on ice and its action on hydraulic structures - Reykjavik, Iceland.
IAHR Secretariat, P. O. Box 177, Delft, the Netherlands

1972 Symposium on ice and its action on hydraulic structures - Leningrad, USSR.
Committee for the USSR Participation in International Power Conferences, 11 Gorky Street, Moscow K-9, USSR

1974 Symposium on river and ice - Budapest, Hungary.
KULTURA (Hungarian Books and News Export-Import Co.)
P. O. Box 149, H-1389 Budapest, Hungary

1975 Symposium on Ice Problems - Hanover, New Hampshire, USA.
Mr. Guenther Frankenstein,
IAHR Symposium on Ice Problems, P. O. Box 282,
Hanover, New Hampshire 03755, USA

1978 Symposium on Ice Problems - University of Lulea, Lulea, Sweden

Arctic Institute of North America (AINA)

1974 The Coast and Shelf of the Beaufort Sea - Published by The Arctic Institute of North America, 3426 North Washington Blvd., Arlington, VA 22201

International Glaciological Society (IGS)

1976 Symposium on Applied Glaciology - Cambridge, England. (Vol. 19, No. 81 Journal of Glaciology, 1977.)

Arctic Ice Dynamics Joint Experiment (AIDJEX)

1977 Symposium on Sea Ice Processes and Models - Published by the University of Washington Press

International Union of Theoretical and Applied Mechanics (IUTAM)

1979 Symposium on the Physics and Mechanics of Ice - Technical University of Denmark, Copenhagen, Denmark. Published by Springer-Verlag

Industry Associations:

USA

Alaska Oil and Gas Association (AOGA)
505 W. Northern Lights Boulevard
Anchorage, Alaska 99503

CANADA

Arctic Petroleum Operator's Association (APOA)
APOA Information Service
P. O. Box 1281
Postal Station M
Calgary, Alberta, Canada T2P 2L2
Publishes ordering information for available APOA projects

Eastcoast Petroleum Operators Association (EPOA)
310, 505 - 8th Avenue S.W.
Calgary, Alberta, Canada T2P 1G2

Government Agencies:

USA U. S. Army Cold Regions Research and Engineering Laboratory (CRREL)
Hanover, New Hampshire 03755

CANADA National Research Council of Canada
Division of Building Research
Ottawa, Canada K1A OR6

Journals:

Journal of Glaciology - International Glaciological Society, Cambridge, England

Cold Regions Science and Technology - Elsevier Scientific Publishing Company, P. O. Box 211, 1000 AE Amsterdam, the Netherlands

Textbooks:

Ice Mechanics - B. Michel, Laval University Press, 1978.

Sea Ice - Yu. P. Doronin and D. E. Kheisin, Translated from Russian for NSF by Amerind Publishing Co., Pvt. Ltd., New Delhi, 1977.

Studies on Ice Physics and Ice Engineering - G. N. Yakovlev, Ed., Translated from Russian by Israel Program for Scientific Translations, Jerusalem, 1973.

Physics of Ice - E. R. Pounder, Pergamon Press, Maxwell House, Fairview Park, Elmsford, N.Y. 1965.

Illustrated Glossary on Snow and Ice - T. Armstrong, B. Roberts, C. Swithinbank, The Scott Polar Research Institute, Lensfield Road, Cambridge, England (Second Edition, 1973).

General Report

National Research Council, Engineering at the Ends of the Earth: Polar Ocean Technology for the 1980's Panel on Polar Ocean Engineering, National Academy of Sciences, Washington, D.C., 1979.

Government Report

U.S. Department of Energy, Report of the Workshop on Arctic Oil and Gas Recovery, held at Sandia National Laboratories, Albuquerque, NM, 30 June - 2 July 1980, edited by William M. Sackinger, University of Alaska; final report DOE Contract No. DE-ACOI-80 ET 14317, September 1980.

SECTION V
CONCLUSIONS AND RECOMMENDATIONS

This section delineates the conclusions and recommendations of the panel that are based on the review and assessment of the material presented in this report. Some conclusions are followed by panel recommendations which are intended to enhance the understanding of sea ice mechanics as related to engineering. The conclusions are presented in the same order as their treatment in the text and not by priority.

Basic Sea Ice Properties

Sea ice properties of strength and moduli depend on state variables such as salinity, temperature, crystal size, and fabric. The engineering values of these properties are not presently well-quantified for use in engineering design. In natural sea ice these variables, and hence properties, are functions of position and time. The properties required for engineering decisions are the integrated values of the local properties. A program to obtain these values requires that properties of small samples be determined for known state variables. Theoretical analysis should be developed to predict the engineering properties of natural ice covers from the results of the small-scale tests. These predictions should be compared to full-scale test data.

RECOMMENDATIONS

Laboratory tests should be conducted to obtain mechanical characteristics of sea ice with appropriate internal states.

Experiments to determine the large scale mechanical characteristics of natural sea ice cover of known internal state should be conducted, and theories should be developed to provide satisfactory properties essential for engineering design.

Properties of Sea Ice Aggregates

The interaction of sea ice types such as sheets, ridges, rubble fields, fragmented ice covers, frazil ice, and brash ice with fixed and moving structures is fundamental to the basis of the engineering design and operation of offshore structures. The mechanical behavior of these sea ice aggregates, as they interact with structures, is not well understood.

RECOMMENDATIONS

> Further knowledge of the mechanical behavior of sea ice aggregates--ice sheets, ridges, rubble fields, fragmented ice covers, frazil ice, and brash ice--should be obtained through field observations. Laboratory studies should be conducted to better understand the formation and interaction of these ice aggregates with engineering structures.
>
> Analytical studies combining field observations and laboratory experiments with the basic laws of mechanics should be conducted to develop theoretical models of the mechanical behavior of these ice types.

Physical Model Testing of Ice

Physical modeling has proven to be a useful way to gain qualitative and quantitative information on a wide variety of problems associated with sea ice mechanics. Such modeling of ice is both much faster and cheaper than corresponding field tests and observations. Therefore, it is important to develop capabilities in this area of modeling sea ice aggregates, and to continue to refine modeling capability in sheet ice.

RECOMMENDATIONS

> A systematic research program should be undertaken to further investigate the properties of different types of materials for modeling of ice. The feasibility of modeling of sea ice aggregates such as ridges and rubble under a variety of failure modes should be determined.

Government and Industry Activities in Sea Ice Research

At the present time, industry supports the brunt of research in sea ice mechanics, while the U.S. government funds research in a few isolated areas. The government-funded research projects are not sufficiently broad nor coordinated to constitute a program leading to a comprehensive understanding of sea ice mechanics.

The prospect of offshore oil and gas energy resource development in the Arctic has created a need to strengthen the government's capability to conduct and support systematic research in sea ice mechanics. The most practicable means of accomplishing this is for one agency to exercise leadership in sea ice research. The ingredients of such leadership include experience in managing and operating ice research programs, assurance of continuous funding support for sea ice research programs, freedom to plan coordinated efforts within the government, with universities, and possibly with industry, and credibility with both government and industry.

No single agency possesses all of these leadership attributes. An interagency committee may improve overall planning. However, a true systematic approach to sea ice research will require the coordination of government planning with industry activities, long-term contractual commitments in support of research, and the focusing of government research in support of national needs.

RECOMMENDATIONS

A lead agency for sea ice mechanics technology should be designated and include in its programs research to answer, in cooperation with other agencies, the pressing engineering problems of sea ice mechanics.

People and Information

A considerable amount of sea ice research is conducted by the private sector; however, there is presently no mechanism to facilitate the public access to research results.

RECOMMENDATIONS

To attract additional people to the field, a long term commitment by the government to support sea ice mechanics research should be indicated. This should include the development of courses, workshops, symposia, and textbooks in the field. A single agency should act as a clearinghouse to facilitate public access to the results of research sponsored by the government and also the private sector (such as research sponsored by the Alaska Oil and Gas Association (AOGA)) that are no longer restricted by security or confidentiality requirements.

Additional Studies

The panel limited its study to the mechanics of sea ice masses of the size equivalent to engineering structures that might be placed in the sea ice environment. The need for further studies is indicated to define completely requirements for offshore engineering and this need is recognized by the Marine Board. The mechanics of sea ice on a geophysical scale of hundreds of kilometers has not been addressed in this report. These geophysical influences determine the large scale motions and stresses in sea ice covers that affect offshore structural design and operations. Also, the collection of large area environmental data has not been addressed.

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